CHAPTER SIX

Water and Sediment Quality: Status and Trends

...in order to continue improvements in the bay's water quality, the next phase of the campaign must be bolder, with deeper societal commitment. We have achieved what in many ways is the easiest part of the cleanup, regulating point source discharges. We must now look at changing the way we think and act.

–Donald R. Baugh, the Chesapeake Bay Foundation

Galveston Bay is arguably the most important estuary on the Texas coast. It harbors the State's largest seaport, houses the world's largest industrial complex, and produces the largest shellfish catch on the Texas coast at 38 percent of the state's total. Thousands of weekend fishermen and boaters use the bay. However, Galveston Bay also receives more industrial and municipal effluent than all the other Texas estuaries and their watersheds combined. Contributions of wastewater from the Houston region, combined with Dallas/Fort Worth wastewater discharged to the Trinity River amount to some 60 percent of the total wastewater generated in the state.

Prior to the mid-1970s, the land-locked portion of the Houston Ship Channel above Morgans Point was listed by the U.S. Environmental Protection Agency (EPA) as one of the ten most polluted bodies of water in the United States. The dissolved oxygen necessary for marine life rarely measured above zero in some areas, rendering them essentially sterile. In 1969, state water quality specialists determined that this water quality degradation caused frequent and massive fish kills downstream in the upper portion of Galveston Bay (U.S. Environmental Protection Agency, 1980).

In response to increasing public concern and pressure from the fledgling Environmental Protection Agency, the Texas Water Quality Board (now the Texas Natural Resource Conservation Commission) initiated several corrective measures to improve the water quality of the Houston Ship Channel and Galveston Bay. Most notable were Operation Clean Sweep, which included detailed monitoring of Ship Channel discharges, and the Galveston Bay Project, the first comprehensive scientific study of the bay. Both of these programs were implemented in the 1968-1972 time period, the era of the Nation's first Water Quality Act.

Stringent discharge goals were established in 1971 for industrial and municipal point sources along Buffalo Bayou and the Houston Ship Channel. All industries discharging to the Houston Ship Channel were ordered to upgrade their wastewater treatment facilities to secondary treatment or better. Between 1973 and 1980, millions of dollars were spent by the Environmental Protection Agency to upgrade and expand municipal waste treatment facilities discharging to the Houston Ship Channel and Galveston Bay. Eventually, the Environmental Protection Agency recognized that several Texas waterways were getting cleaner and singled out the Houston Ship Channel as "the most notable improvement, a truly remarkable feat" (U.S. Environmental Protection Agency, 1980). Additional investments in wastewater treatment since 1980 have continued to improve water quality in the Houston Ship Channel.

Galveston Bay itself has never experienced the serious water quality problems observed in the Houston Ship Channel, even during the 1960s and 1970s. The open bay is shallow, well-mixed, well-aerated by prevailing winds, and flushed more than four times a year by fresh water inflow and the tides. Therefore, one of the main features of Galveston Bay is that the open bay historically maintained good water quality, while serious water quality problems have been concentrated in the western urban tributaries to the bay, particularly the ship channel.

This chapter deals with the present status and historical trends of water and sediment quality in the bay as well as quantification of the main sources of pollutants to the bay. Point and nonpoint source contributions are discussed as well as localized specific problem areas such as marinas and brine discharges resulting from petroleum production. An analysis of the major pollutant sources and observed cause-and-effect mechanisms over the past 20 years is also presented. A significant conclusion is the identification of nonpoint sources as the greatest contributor of some pollutants to the bay system.

REVIEW OF WATER AND SEDIMENT QUALITY PARAMETERS

Quantifying water and sediment quality in an estuary requires measurement of a suite of physical and chemical properties, termed "parameters." Some parameters serve as indicators, (indirect measures of pollutants that could not be measured directly, such as fecal coliform bacteria and biochemical oxygen demand or BOD). Other parameters play major roles in biochemical processes, for example nitrogen and phosphorus compounds, or toxic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and pesticides. Finally, some of the parameters, such as salinity, serve as both indicators and take on important roles in biological processes.

For the purposes of this discussion, water and sediment quality parameters have been divided into two categories: pollutants and water/sediment quality indicators. This division is arbitrary and was used to simplify the discussion.

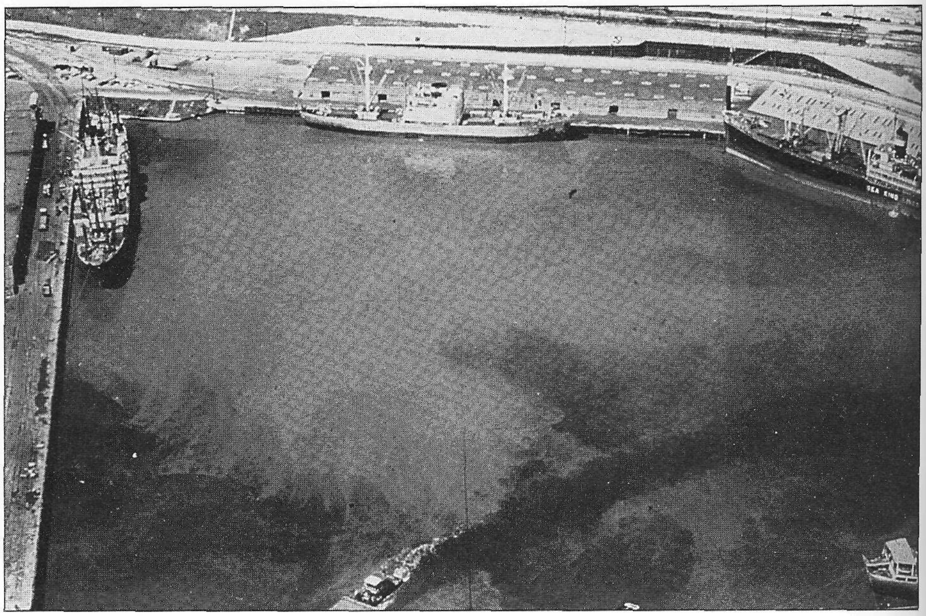
Types of Pollutants

Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD or BOD_5) is an indirect measure of biodegradable organic compounds in water, and is determined by measuring the dissolved oxygen decrease in a controlled water sample over a five-day period. During this five-day period, **aerobic** (oxygen-consuming) bacteria decompose organic matter in the sample and consume dissolved oxygen in proportion to the amount of organic material that is present. In general, a high BOD reflects high concentrations of substances that can be biologically degraded, thereby consuming oxygen and potentially resulting in low dissolved oxygen in the receiving water. The BOD test was developed for samples dominated by oxygen-demanding pollutants like sewage. While its merit as a pollution parameter continues to be debated, BOD has the advantage of a long period of record.

Nutrients

Nutrients are chemical elements or compounds essential for plant and animal growth. Nutrient parameters include ammonia, organic nitrogen, Kjeldahl nitrogen, nitrate nitrogen (for water only) and total phosphorus. High amounts of nutrients have been associated with eutrophication, or overfertilization of a water body, while low levels of nutrients can reduce plant growth and (for example) starve higher level organisms that consume phytoplankton. In Galveston Bay, nitrogen is generally considered to be the "limiting nutrient," i.e., the most important nutrient that actually controls plant growth in the system, because of its low and limiting concentrations compared to other nutrients (see the Chapter Eight discussion of phytoplankton).



Source: Texas Natural Resource Conservation Commission

Water quality in the upper Houston Ship Channel has improved over the past 25 years. During the early 1970s when this photograph of the turning basin was taken, dissolved oxygen and living organisms were non-existent over wide areas. Now, thanks to pollution abatement programs, some species have returned, and the most serious dissolved oxygen problems are near the bottom, rather than throughout the entire water column.

Organic Carbon

Most organic carbon in water occurs as partly degraded plant and animal materials, some of which are resistant to microbial degradation. Organic carbon is important in the estuarine food web and is incorporated into the ecosystem by photosynthesis of green plants, then consumed as carbohydrates and other organic compounds by higher animals. In another process, formerly living tissue containing carbon is decomposed as detritus by bacteria and other microbes. **Total organic carbon** (TOC) bears a direct relationship with biological and chemical oxygen demand; high levels of TOC can result from human sources, the high oxygen demand being the main concern. Carbon processes involving both organic and inorganic forms are vital in bay biology and chemical cycling.

Oil & Grease

Oil and Grease constitutes one of the most common parameters for quantifying organics from human sources and, to a lesser extent, **biogenic** sources (e.g., algae and fish). Some examples of oil and grease loadings to Galveston Bay are leaks from automobile crankcases, illegal dumping into storm sewers, motorboats, oil spills, and discharge from oil production platforms in the bay. Oil and grease is a generic term for material which actually contains numerous and variable chemical compounds, some of which are typically toxic.

Priority Pollutants

Priority Pollutants refer to a list of 126 specific pollutants that includes heavy metals and specific organic chemicals. The priority pollutants are a subset of "toxic pollutants" as defined in the Clean Water Act. These 126 pollutants were assigned a high priority for development of water quality criteria and effluent limitation guidelines because they are frequently found in wastewater. Many of the heavy metals, pesticides, and other chemicals listed below are on the priority pollutant list.

Heavy Metals (Total and Dissolved)

Heavy metals are elements from a variety of natural and human sources. Some key metals of concern and their primary sources are listed below (Cole et al., 1984):

Arsenic (from fossil fuel combustion and industrial discharges);

Cadmium (from corrosion of alloys and plated surfaces, electroplating wastes, and industrial discharges);

Chromium (from corrosion of alloys and plated surfaces, electroplating wastes, exterior paints and stains, and industrial discharges);

Copper (from corrosion of copper plumbing, anti-fouling paints, and electroplating wastes);

Lead (from leaded gasoline, batteries, and exterior paints and stains);

Mercury (from natural erosion and industrial discharges); and

Zinc (from tires, galvanized metal, and exterior paints and stains).

High levels of mercury, copper, and cadmium have been proven to cause serious environmental and human health problems in some bays around the world. Some of the sources listed above, such as lead in gasoline and heavy metals in some paints, are now being phased out by environmental regulations issued in the past ten years.

Pesticides

Pesticides comprise a large class of compounds of concern in Galveston Bay. Typical pesticides and herbicides include DDT, Aldrin, Chlordane, Endosulfan, Endrin, Heptachlor, and Diazinon. Surprisingly, concentrations of pesticides in urban runoff may be equal or greater than the pesticides in agricultural runoff in the bay area (Newell et al., 1992). Besides toxicity, persistence in the environment is a key concern. Some of the more persistent compounds including DDT and dioxin (not a pesticide) are subject to stringent regulation including outright bans.

Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic Aromatic Hydrocarbons include a family of semi-volatile organic pollutants such as naphthalene, anthracene, pyrene, and benzo(a)pyrene. There are two main sources of PAHs to Galveston Bay: spilled or released petroleum products (from oil spills or discharge of oil production brines) and combustion products that are found in urban runoff. Specifically, phenanthrene, pyrene, and fluoranthene are products of the incomplete combustion of fossil fuels. Naphthalene is found in asphalt and creosote. PAHs from combustion products have been identified as a source of some carcinogenic risk for eating seafood caught in Galveston Bay (see Chapter Nine).

Polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls are organic chemicals that formerly had widespread use in electrical transformers and hydraulic equipment. This class of chemicals is extremely persistent in the environment and has been proven to **bioconcentrate** in the food chain, thereby leading to environmental and human health concerns in areas such as the Great Lakes. Because of the potential to accumulate in the food chain, PCBs were intensely regulated and subsequently prohibited from manufacture by the Toxic Substances Control Act (TSCA) of 1976. Disposal of PCBs is tightly restricted by TSCA. As with PAHs, PCBs have been identified as a source of some carcinogenic risk through ingestion of seafood from Galveston Bay (see Chapter Nine).

Key Water Quality Indicators

Temperature

Temperature of water in an estuary is important to many of the bay's chemical, physical, and biological processes. One of the important effects of temperature is on the rate of chemical and biological reactions, for example the solubility of oxygen in water increases as temperature decreases. Of course, aquatic organisms die when the water temperature falls below a certain level (e.g., 0°C for most species) or when it exceeds a maximum value (about 35°C for many finfish).

pH

pH is a measure of the state of equilibrium between water (H_2O) and its ions (H^+) and (OH^-) and is determined by various dissolved compounds in water, including salts and gasses. When compounds having ionizable H^+ or OH^- groups dissolve in water, the equilibrium between H_2O, H^+, and OH^- shifts and the pH value increases (becomes more basic) or decreases (becomes more acidic). pH reflects the reactivity of water with various pollutants, and therefore the toxicity of those pollutants. Generally, pH exhibits low variability in coastal situations due to the high buffering capacity of seawater. Departures from the normal range of seven to nine are therefore especially significant.

Salinity and Related Parameters

Salinity is one of the quintessential properties of estuarine waters, being fundamentally determined by the intermixing of fresh and oceanic waters. As a conservative parameter, it is an excellent indicator of circulation in an estuary (see Chapter Five). It is also a key ecological indicator, since it affects the suitability of habitats due to varying **osmoregulation** capabilities of organisms. One of the most common methods of estimating salinity of a water sample is measurement of its electrical conductivity. For a given temperature, conductivity of water varies linearly with ion concentration, making measurement of electrical current between two submerged electrodes a convenient measurement. An additional indicator of salinity is the refractive index of water, which is measured with a portable refractometer. The refractometer is calibrated for a direct read-out of salinity. Salinity is generally expressed in parts per thousand (ppt).

Turbidity and Related Parameters

Turbidity is the converse of water clarity–referring to interference with the passage of light by suspended matter, soluble colored organic compounds, or plankton in the water. The measurement of turbidity is used as an indirect indicator of the concentration of suspended matter, and also is important for evaluating the available light for photosynthetic use by aquatic plants and algae. One method of measuring turbidity is with an electronic transmissiometer, which measures light attenuation in water optically, yielding a percent transmittance. A much simpler, traditional method is use of a Secchi disc (a Secchi disc is a black and white disc which is lowered in water to the point where it is just barely visible in order to measure the depth of light penetration). The long-term average Secchi depth for Galveston Bay is about half a meter, extremely turbid in comparison to east and west coast situations.

Total Suspended Solids (TSS)

Total suspended solids refers to the concentration of suspended solid matter in water. TSS is measured by weighing the undissolved material trapped on a 0.45 micrometer filter after filtration. The constituents that pass through the filter are designated **total dissolved solids** (TDS) and are comprised mainly of ions such as iron, chloride, sodium, sulfate, etc. It should be noted that there is a direct proportional relationship between suspended solids and turbidity. The solids in suspension may include sediment or detrital particles and plankton.

Dissolved Oxygen and Related Parameters

Dissolved oxygen (DO) is the traditional and ubiquitous indicator of aquatic health. It determines the ability of aerobic organisms to survive, and in most cases higher dissolved oxygen is better. The concentration of dissolved oxygen depends upon temperature (an inverse relationship), salinity, wind and water turbulence, atmospheric pressure, the presence of oxygen-demanding compounds and organisms, and photosynthesis. Of these, DO is introduced into the water column principally through **reaeration**, (simple mechanical agitation by wind) and through photosynthesis.

Dissolved oxygen *deficit* is the difference between the capacity of the water to hold oxygen and the actual amount of DO in the water (the converse of percent saturation). A large deficit is an indicator of some oxygen demanding stress on natural waters, while a low deficit is an indicator of generally unstressed conditions (DO gives no indication of possible toxic contamination). A DO saturation greater than 100 percent can occur when the water is supersaturated with oxygen, a temporary condition that typically results from rapid photosynthesis. This is not uncommon during colder winter months when water temperatures are low.

Chlorophyll-a

Chlorophyll-*a* reflects the concentration of the principal pigment in green plants responsible for photosynthesis. As such, this parameter is a surrogate indicator of phytoplankton biomass, the amount of unattached single-celled algae that is present in the water (see Chapter Eight).

Fecal Coliform Bacteria

Fecal coliforms are present in the intestines or feces of warm blooded animals in normal numbers of about a million per gram of feces. Fecal coliforms are used as the primary indicator for determining if the water is contaminated by animal or human waste. Although fecal coliforms do not normally cause illness in humans, their presence suggests that other potentially dangerous pathogens could also be present. A fecal coliform standard of less than 2000 colonies per 100 mL has been established for non-contact recreation sports such as sailing. A standard of less than 200 colonies per 100 mL was established for contact recreation such as swimming. Fecal coliform counts below 14 colonies per 100 mL comprise the standard for shellfish harvesting. Chapter Nine presents a detailed discussion of fecal coliform bacteria, their limitations as an indicator organism, and public health implications related to Galveston Bay.

Relationships Among Parameters

In determining estuarine water quality, several different parameters can sometimes be interpreted to measure the same essential property. For example, salinity (an essential property) can be estimated from measurements of chlorides concentration, total dissolved solids, density, conductivity, or light refraction. Different data collection programs in the bay may employ different measures, depending upon objective, convenience and tradition (Ward and Armstrong, 1992).

Relationships among parameters are important for two reasons. First, one parameter may have conceptual advantages over another, e.g., DO deficit may be more indicative of the effects of pollutant loading and biological activity than the concentration of dissolved oxygen itself (because the deficit normalizes the effects of temperature and salinity on the solubility of DO in water). Second, measurements of one parameter can frequently be used to estimate another, providing a means to establish a denser, longer-term data set by converting various parameters to a common measurement. Since no two parameters are completely interchangeable, this process requires caution. To establish whether such relations are justified for a given class of parameters is a central step in a long-term trend analysis. In this chapter, for example, these "proxy" relationships were utilized by Ward and Armstrong (1992) to improve the density of long-term data sets for salinity, BOD, DO, DDT, turbidity, nitrogen, phosphorus, and coliforms.

WATER QUALITY SEGMENTS AND BAY MONITORING PROGRAMS

Segmentation refers to the subdivision of the estuary into regions. The Galveston Bay system, including the tributaries, is presently subdivided into about 40 different geographic segments by the Texas Natural Resource Conservation Commission (FIGURE 6.1). The agency's Water Quality Segments (also referred to as Classified Segments or Designated Segments) are the basis for evaluating waste load capacity and for setting water quality standards (TABLE 6.1), hence they underlie discharge permitting, compliance enforcement, and administrative actions. In the monitoring realm, the Water Quality Segments are the basis for establishing the geographic location of monitoring stations and for determining the **ambient** water and sediment quality of particular areas.

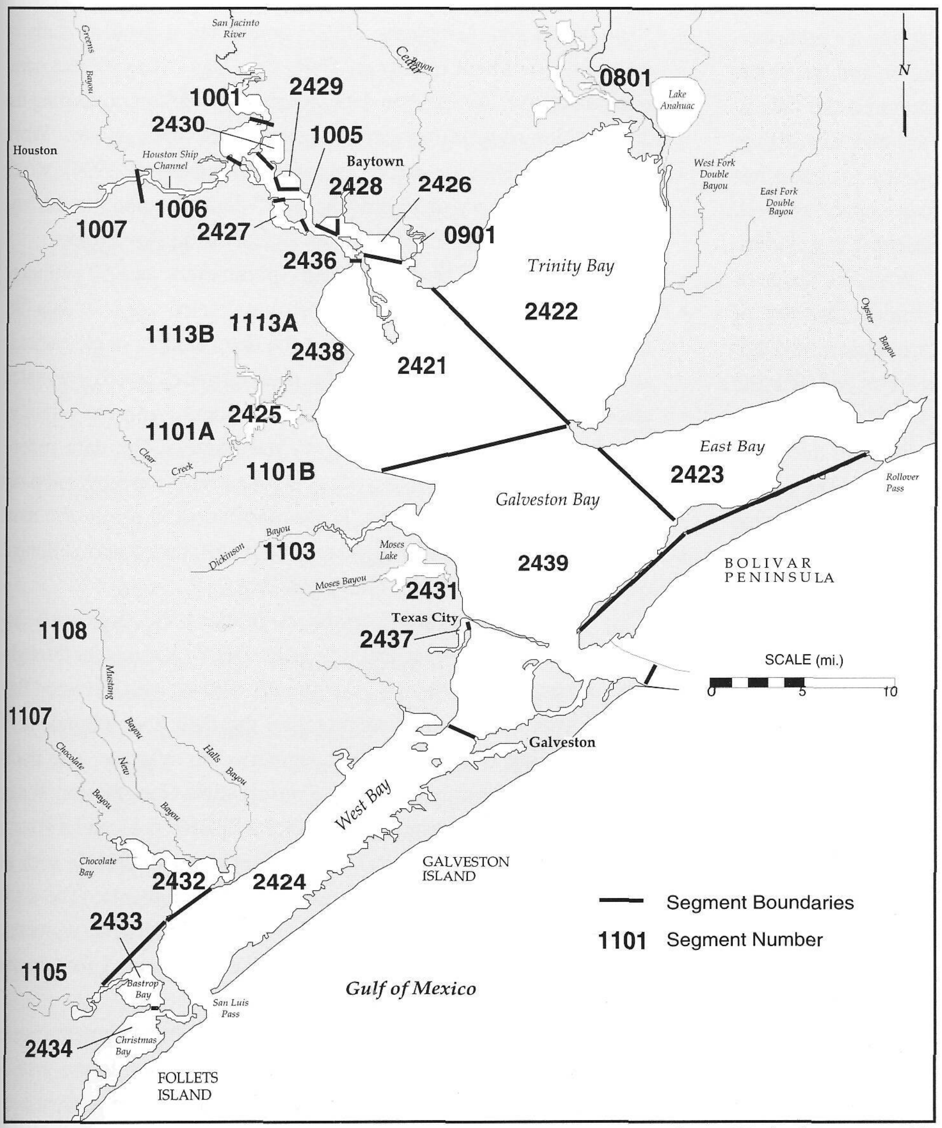
Existing monitoring programs are of central importance to Galveston Bay, since these are the means for continued, routine acquisition of data to determine water quality and its trends. Currently, four major monitoring programs contribute information on water and sediment quality of the bay. These programs are operated and maintained independently by the following agencies:

Texas Natural Resource Conservation Commission ;

Texas Parks and Wildlife Department;

Texas Department of Health; and

U. S. Geological Survey.



Source: Ward and Armstrong, 1992

FIGURE 6.1. Texas Natural Resource Conservation Commission Water Quality Segments for Galveston Bay. Future regional monitoring of the bay system may require further subdivision of some segments in order to increase the resolution of the information available to resource managers.

The Texas Natural Resource Conservation Commission maintains the Surface Water Quality Monitoring database, a principal source of continuous broad-spectrum environmental data on the state's surface waters. This program includes water, sediment, and biological measurements acquired at fixed stations at regular intervals. Generally, field parameters are obtained *in situ*, by means of instrument probes or portable analytical kits. Once collected, shipped to the laboratories of the Texas Natural Resource Conservation Commission and/or Texas Department of Health for analysis. Parameters have been expanded from a few conventional variables in the early 1970s to include trace constituents, pesticides and priority pollutants (toxicants) in recent years.

Surface water quality monitoring data are accessible through the Texas Natural Resource Conservation Commission Regulatory Activities & Compliance System (TRACS), a data management system operated by the agency and also accessible through the Texas Natural Resources Information System of the Texas Water Development Board. In addition to a compilation of all sampling data from the Surface Water Quality Monitoring Program, TRACS also contains data from special studies and intensive surveys (most of the data in the TRACS database is also in Environmental Protection Agency's STORET database). TRACS also includes data from other agencies, notably the Texas Water Development Board and U. S. Geological Survey.

The Texas Parks and Wildlife Department and its predecessor agencies (the Texas Game and Fish Commission and the Texas Game, Fish and Oyster Commission), have monitored the fishery resources of the system for many years (see Ward and Armstrong, 1992). In association with biological sampling, the program has obtained a limited suite of water quality measurements as well. These tend to focus on estuarine habitat characteristics, e.g., salinity, dissolved oxygen, turbidity and temperature. While the range of water quality variables is obviously much more limited than that of the Texas Natural Resource Conservation Commission, the frequency of sampling is much greater. The Texas Parks and Wildlife Department obtains data virtually on a daily basis, however the sample stations are randomized for statistical reasons so that there is no sampling continuity at any fixed point in the bay. The data is entered into a digital data base at agency headquarters for detailed statistical analyses.

The Shellfish Sanitation Division of the Texas Department of Health samples the bay at regular stations with varying frequency, depending upon season and recent rains that could affect bacterial concentrations. Texas Department of Health sampling is now limited to fecal coliform bacteria and a few associated hydrographic variables, salinity, temperature and pH. Like the Texas Parks and Wildlife Department, this program samples more intensely in space and time than the Surface Water Quality Monitoring program of the Texas Natural Resource Conservation Commission, and has accumulated data over many years from Galveston Bay. The collected data is maintained in a digital database at Texas Department of Health headquarters in Austin.

The activities of the U. S. Geological Survey emphasize the quantity and quality of inflow to the bay, though the Houston office also performs sampling within the estuary itself to help meet the needs of other federal and state agencies. This data is published annually and is maintained in a digital database. Data collected in support of other agencies may be managed differently, depending upon the nature of the data and the needs of the sponsoring agency.

There are other important data collection programs in Galveston Bay that deserve mention even though they are not *monitoring* programs. These include: 1) the sediment quality sampling performed by the Galveston District Corps of Engineers in association with its Operations and Maintenance Program for navigation; 2) the first Galveston Bay Project–a comprehensive program conducted by the Texas Water Quality Control Board involving monthly sampling at a network of fixed stations; 3) the sampling conducted in the Submerged Lands Study of the University of Texas Bureau of Economic Geology, sponsored by the Texas General Land Office; 4) sampling by the Texas Department of Health; 5) sampling completed by the U. S. Bureau of Commercial Fisheries; and 6) the Datasonde data collection program sponsored by the Texas Water Development Board. Data from these programs has contributed to the findings summarized in the next section of this chapter.

WATER QUALITY

Ward and Armstrong (1992) conducted a detailed study of water and sediment quality in Galveston Bay. The project compiled data from 26 separate data collection programs, including the three major state monitoring programs described above. Work began with a Data Inventory (Ward and Armstrong, 1994), which resulted in recovery of significant "lost" data pertaining to the bay, including some data from the 1968-72 Galveston Bay Project.

For each of 73 water quality parameters and 50 sediment quality parameters, Ward and Armstrong created a master data file. Each record in these files included the date, sample depth, latitude and longitude of the station, the measurement itself, estimated uncertainty of measurement, and a code identifying the origin of the data. For most water quality parameters, the data record extends back at least two decades, and for a few conventional parameters, back to the 1950s. This compilation is easily the most extensive and detailed long-term record of water and sediment quality ever assembled for Galveston Bay.

The study characterized the magnitudes and large-scale distributions of major water and sediment quality parameters throughout Galveston Bay. Spatial variation throughout the Galveston Bay system was addressed by aggregating the data into subregions of the bay, using two independent segmentation systems: the traditional Texas Natural Resources Conservation Commission Water Quality Segments described above (see FIGURE 6.1), and a system of "Hydrographic Segments" based upon physical criteria such as regions of homogeneity and locations of key gradients. The maps presented in this chapter are based on the hydrographic segments, which show higher resolution than Texas Natural Resources Conservation Commission segments.

Statistical trends in each of the different segments were mapped (FIGURES 6.2–6.11) using the following rules: a *probable* increasing or decreasing trend corresponded to 95 percent confidence boundaries on the slope of the time regression; a *possible* increasing or decreasing trend corresponded to 80 percent confidence boundaries. Since each hydrographic segment contains its own data sets and is analyzed separately, a pattern of consistent

TABLE 6.1. Present Texas Natural Resource Conservation Commission Water Quality Segments, Designated Uses, and Standards in the Galveston Bay System.

Segment Number	Segment Name	Designated Uses[1]								Standards	
		cr	hqh	sfw	iws	ncr	iqh	pwds	nav	DO	FC
2421	Upper Galveston Bay	•	•	•						4.0	14
2422[2]	Trinity Bay	•	•	•						4.0	14
2423	East Bay	•	•	•						4.0	14
2424	West Bay	•	•	•						4.0	14
2425	Clear Lake	•	•							4.0	200
2426	Tabbs Bay	•	•							4.0	200
2427	San Jacinto Bay	•	•							4.0	200
2428	Black Duck Bay	•	•							4.0	200
2429	Scott Bay	•	•							4.0	200
2430	Burnett Bay	•	•							4.0	200
2431	Moses Lake	•	•							4.0	200
2432	Chocolate Bay	•	•	•						4.0	14
2433	Bastrop Bay/Oyster Lake	•	•	•						4.0	14
2434	Christmas Bay	•	•	•						4.0	14
2435	Drum Bay	•	•	•						4.0	14
2436	Barbours Cut	•	•							4.0	200
2437	Texas City Ship Channel		•			•				4.0	200
2438	Bayport Channel		•			•				4.0	200
2439	Lower Galveston Bay	•	•	•						4.0	14
Trinity River											
0801	Trinity River Tidal	•	•							4.0	200
0802	Trinity River below Lake Livingston	•	•					•		5.0	200
Trinity–San Jacinto Coastal											
0901	Cedar Bayou Tidal	•	•							4.0	200
0902	Cedar Bayou Above Tidal	•	•					•		5.0	200
Houston Ship Channel/San Jacinto River											
1001	San Jacinto River Tidal	•	•							4.0	200
1005	HSC/San Jacinto River		•			•				4.0	200
1006	HSC				•				•	2.0	2000
1007	HSC/Buffalo Bayou				•					1.0	2000
1013	Buffalo Bayou Tidal	•					•			3.0	200
1014	Buffalo Bayou Above Tidal	•					•			—	—
San Jacinto-Brazos Coastal											
1101[2]	Clear Creek Tidal	•	•							4.0	200
1102[2]	Clear Creek Above Tidal	•	•							5.0	200
1103	Dickinson Bayou Tidal	•	•							4.0	200
1104	Dickinson Above Tidal	•	•					•		4.0	200
1105	Bastrop Bayou Tidal	•	•							4.0	200
1107	Chocolate Bayou Tidal	•	•							4.0	200
1108	Chocolate Bayou Above Tidal	•	•							5.0	200
1113	Armand Bayou Tidal	•	•							4.0	200

Source: Galveston Bay National Estuary Program

[1]Note:
cr = contact recreation, ncr = non contact recreation,
hqh = high quality habitat, iqh = intermediate quality habitat,
sfw = shellfish waters, pdws = public domestic water supply,
iws = industrial water supply, FC = fecal coliform, colonies/100mL,
DO = dissolved oxygen, mg/L, nav = navigation

[2]Segments 1101, 1113, and 2422 are subdivided, constituting a total of seven segments

trends from segment to segment in a region of the bay strengthens the statistical "reality" of the computed trend (Ward and Armstrong, 1992). For these analyses, measurements in the data set designated "below detection limit" were assigned a value of zero.

Water Quality Status and Trends

Temperature

Temperature in the bay was generally homogeneous with little systematic stratification (depth variation), due to shallow depths in the bay and the prominence of mixing due to wind. The principal source of variation in temperature was variation among seasons. Average summer temperatures for the bay (FIGURE 6.2a) ranged from approximately 29°C (84°F) to greater than 31°C in a few locations. Summer temperatures as low as ten °C and as high as 39°C were recorded in some segments of the bay. FIGURE 6.2a also shows the effect of power plants on bay temperature: the Cedar Bayou Generating Station appears to have increased water temperature near its northeast Trinity Bay **outfall** by 0.3°C, while the P.H. Robinson plant may have increased the temperature of middle Galveston Bay above Eagle Point by about 0.7°C. Statistical trends for summer temperatures are shown in FIGURE 6.2b, where a general reduction of about two °C over the past thirty years was observed. Because the average temperatures shown are based on 30 years worth of data, the average temperature today is probably as much as one to two °C lower than the average temperature shown in FIGURE 6.2a.

Although not shown in the figures, average temperatures for the bay during winter conditions (December through February) ranged from approximately ten °C to greater than 16°C in a few locations. Winter temperatures as low as zero °C and as high as 29°C were recorded in some segments of the bay .

Salinity

Salinity gradients from the upper to lower bay are a normal feature, with Gulf inlet values of about 30 ppt declining to about three ppt near principal points of inflow such as the Trinity River. Vertical salinity stratification of bay waters was slight compared to East and West Coast estuaries, generally averaging less than 0.6 ppt/m, with about half the bay less than 0.3 ppt/m. Salinity stratification did not correlate with depth in the bay as a whole, but the Houston Ship Channel tends to serve as a conduit for Gulf water to intrude into the upper bay system. Salinity data and trends for the upper 1.5 m of the bay are shown in FIGURES 6.3a and 6.3b. Increasing salinity was observed in parts of upper Trinity Bay, while a widespread decline in salinity was observed, particularly in the lower bay. An additional discussion on the relationship between circulation and salinity is provided in Chapter Five.

Total Suspended Solids (TSS)

Total suspended solids data for Galveston Bay are depicted in FIGURE 6.4a and the statistical trends over time are shown in FIGURE 6.4b. Generally, TSS concentrations in the bay varied from less than ten mg/L to greater than 60 mg/L in a few of the segments. The data in FIGURE 6.4b show that the general trend in TSS throughout the bay was an overall decrease over the past 20 years.

Dissolved Oxygen (DO)

Dissolved oxygen was generally high throughout Galveston Bay, averaging near-saturation across large areas (FIGURE 6.5a), with frequent occurrences of concentrations greater than the equilibrium concentration with air (**supersaturation**). Exceptions to this were in poorly flushed tributaries subjected to inflow and waste discharges, the most significant of which was the Houston Ship Channel.

Trends in the DO deficit are shown in FIGURE 6.5b; data indicated a strong decreasing trend in the upper Houston Ship Channel of about 0.1 mg/L per year over the past 20 years. There was no statistical trend over much of the middle bay, but an increase in oxygen deficit (a lowering of the oxygen concentration) occurred in the following areas: the outlet of the Trinity River, the outlet of Clear Lake, and East Bay-lower Galveston Bay.

Total Phosphorus

Total phosphorus concentrations ranged from less than 0.2 mg/L to greater than two mg/L (FIGURE 6.6a). The general trend in total phosphorus data was one of decline, shown in FIGURE 6.6b.

Nitrate (NO_3)

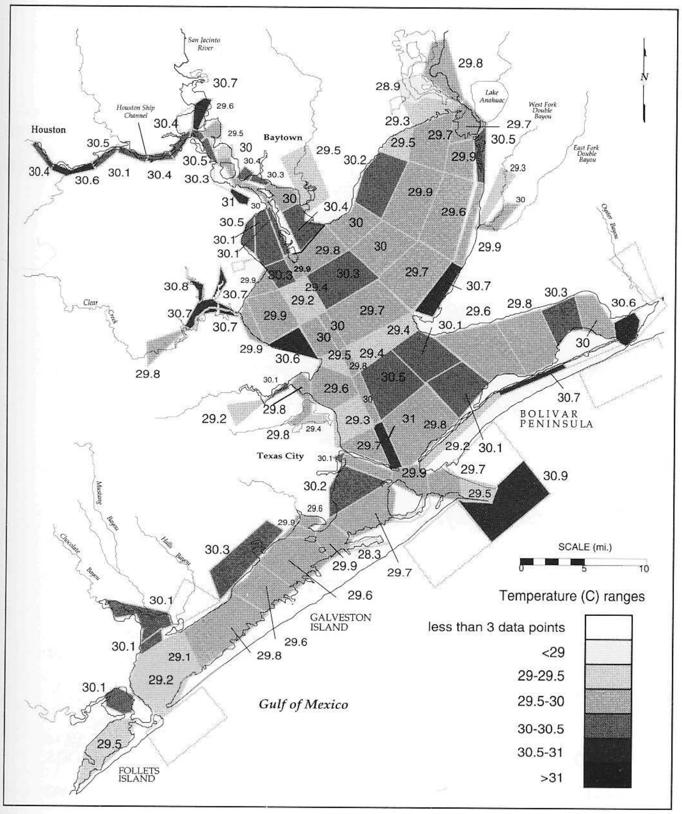
Nitrate concentrations ranged from 0.1 mg/L to greater than 0.5 mg/L (FIGURE 6.7a) with the average value falling in the middle range for U.S. estuaries. The general trend was a decline throughout most of the bay (FIGURE 6.7b). One area of increasing nitrate concentration was the Houston Ship Channel, which can be interpreted as an improvement: where most plants once discharged the majority of their non-organic nitrogen as ammonia, they now nitrify the ammonia and discharge the oxidized form of nitrogen as nitrate. This change corresponds to discharge permit requirements for secondary treatment and other process improvements. It should be noted, however that nitrate is an important source of nutrients for phytoplankton production. Too much nitrate can cause eutrophic conditions.

Ammonia

Ammonia concentrations ranged from 0.2 mg/L to greater than two mg/L. Many areas of the bay show an uncertain time trend for this parameter, but where trends occurred, they tended to reveal a decline in ammonia concentrations. A clear ammonia decline in the upper Houston Ship Channel due to wastewater treatment improvements is discussed later in this chapter.

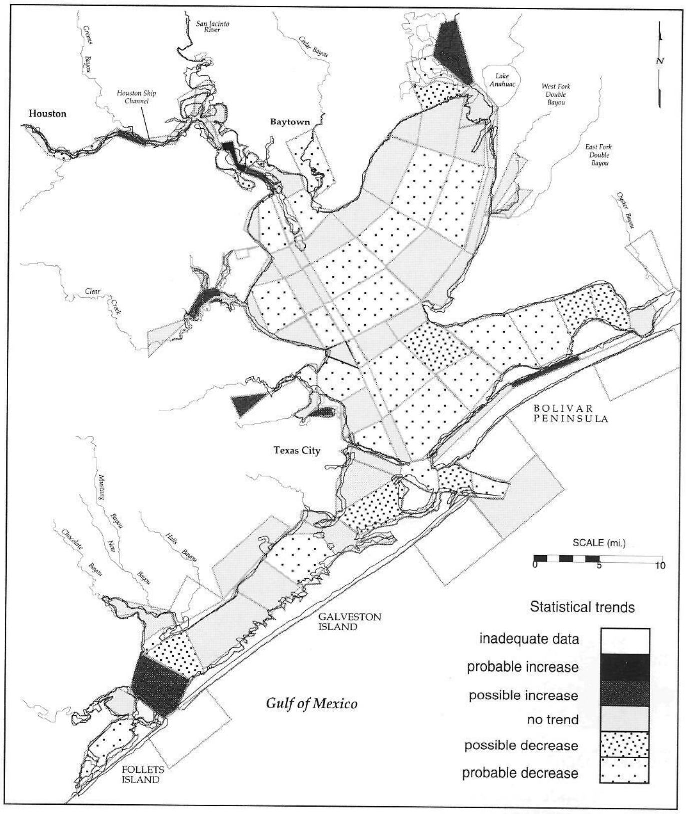
Chlorophyll-a

Concentrations ranged from less than ten µg/L to over 50 µg/L (FIGURE 6.8a) with the average value falling in the middle range for U.S. estuaries. Chlorophyll-*a* concentrations exhibited a clear declining trend throughout much of the bay (FIGURE 6.8b).



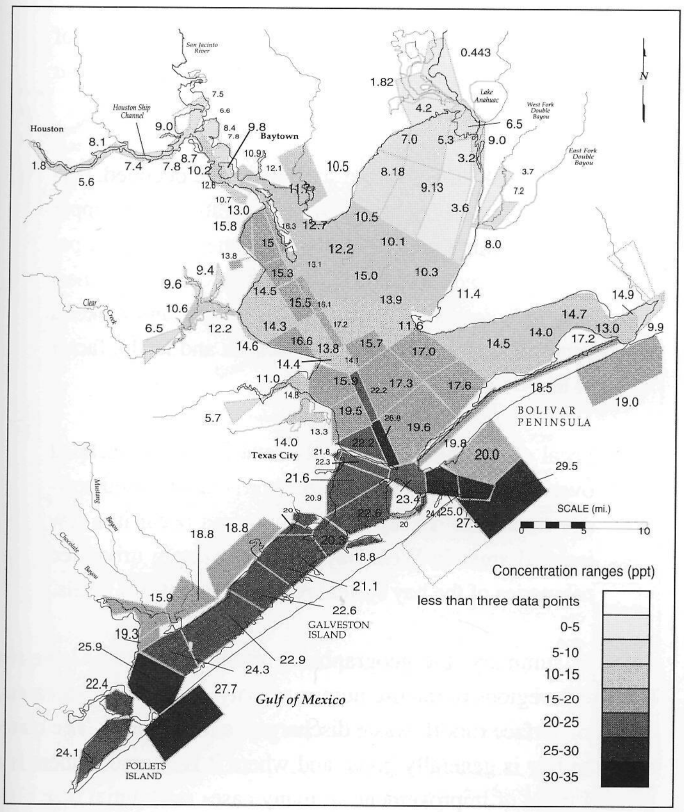
Source: Ward and Armstrong, 1992

FIGURE 6.2a. *Average summer water temperature in the upper 0.5 m of Galveston Bay, 1950-1991.*



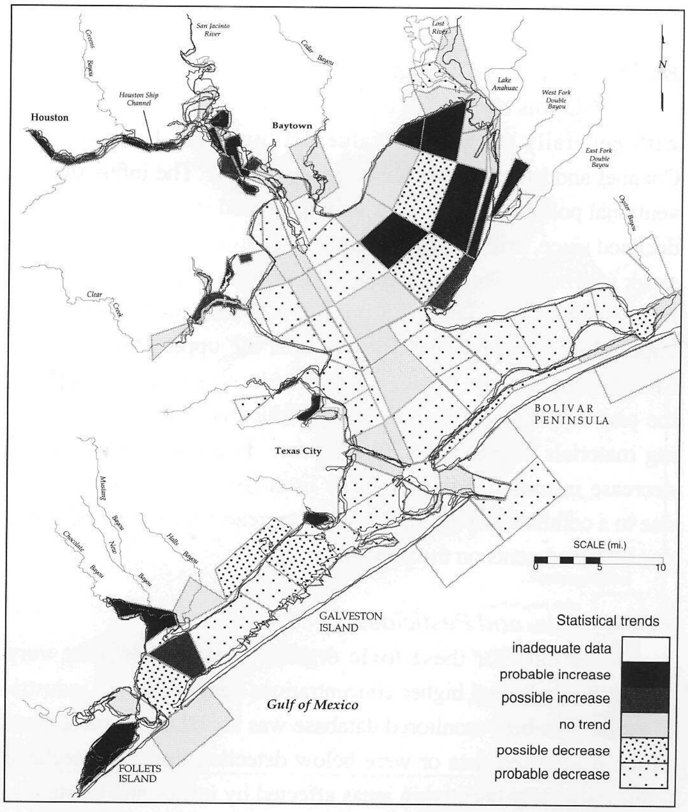
Source: Ward and Armstrong, 1992

FIGURE 6.2b. *Statistical trends for summer water temperature in the upper 0.5 m of Galveston Bay, 1950-1991.*



Source: Ward and Armstrong, 1992

FIGURE 6.3a. *Average salinity in the upper 1.5 m of Galveston Bay, 1950-1991.*



Source: Ward and Armstrong, 1992

FIGURE 6.3b. *Statistical trends for salinity in the upper 1.5 m of Galveston Bay 1950-1991.*

A discussion of the significance of this decline is presented in the Chapter Eight discussion on phytoplankton.

Fecal Coliform Bacteria

Fecal coliform bacteria concentrations ranged from less than ten organisms per 100 mL to greater than 100,000 organisms per 100 mL in the vicinity of the upper Houston Ship Channel (FIGURE 6.9a). Long-term average fecal coliform concentrations were low in most locations but exceedances of state criteria by individual measurements were not unusual (See Chapter Nine). The trend in concentrations over time varied across the bay, with a general decline in the Houston Ship Channel and some increases in West Bay (FIGURE 6.9b).

Oil and Grease

Oil and Grease concentrations ranged from less than two mg/L up to 20 mg/L (FIGURE 6.10a). Highest concentrations were centered around the Houston Ship Channel, Texas City, and the inlet to Galveston Bay. The database for oil and grease is so incomplete that Ward and Armstrong (1992) were unable to determine any definite trends over much of the bay (FIGURE 6.10b).

Total Copper

Concentrations ranged from less than 20 µg/L to over 100 µg/L (FIGURE 6.11a). The database for total copper measurements is not complete enough to determine trends (FIGURE 6.11b). Note that there is some controversy over the validity of copper and other metals data (see metals discussion on page 110).

Biological Oxygen Demand

BOD was elevated in regions of runoff and waste discharge, with generally the highest values in the upper Houston Ship Channel and lowest values in open bay waters. The influx of conventional pollutants from point sources peaked in the 1960s and has declined since, primarily due to implementation of advanced wastewater treatment. For example, a 20-fold reduction has occurred in BOD loading since about 1970 (see FIGURES 6.12 and 6.27 for upper Houston Ship Channel). Within the upper Houston Ship Channel, the average DO deficit was reduced about four mg/L in the past 20 years, mainly due to the reduction in oxygen-demanding materials discharged in wastewater. In addition, there was a decrease in mass loading of BOD from river and stream inflows due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers.

PCBs, PAHs, and Pesticides

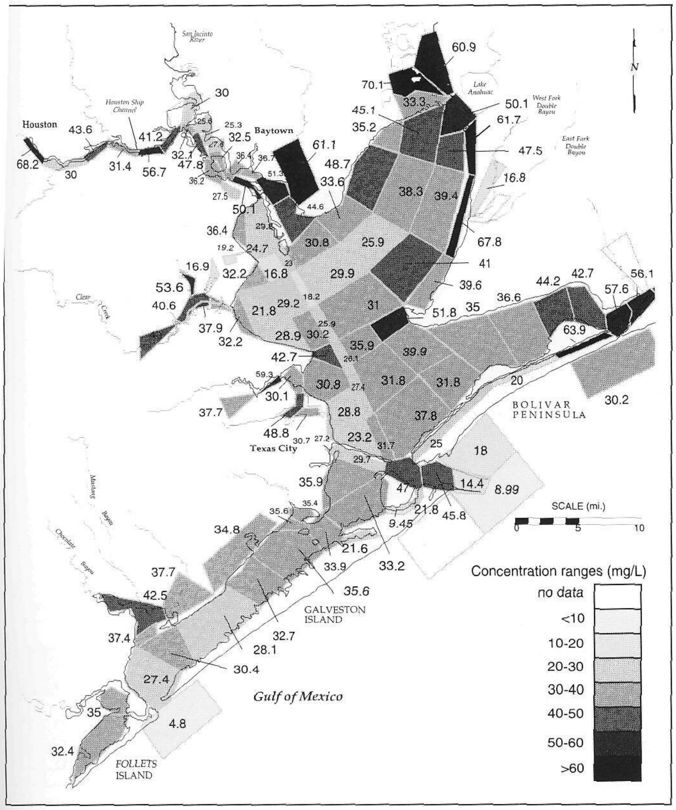
The data for these toxic organic constituents were very sparse, but indicated higher concentrations near urban and industrial areas. The best-monitored database was for DDT but most areas of the bay lacked data or were below detection limits. Detectable values generally occured in areas affected by inflow and waste discharges like the Houston Ship Channel, Clear Creek, and Texas City Turning Basin. Concentrations below detection limits were recorded in the San Jacinto River, Chocolate Bay and Cedar Bayou. No time trends were computed due to the sparse data.

Summary of Water Quality Trends

Ward and Armstrong (1992) summarized major alterations in water quality in the Galveston Bay system over the last several decades:

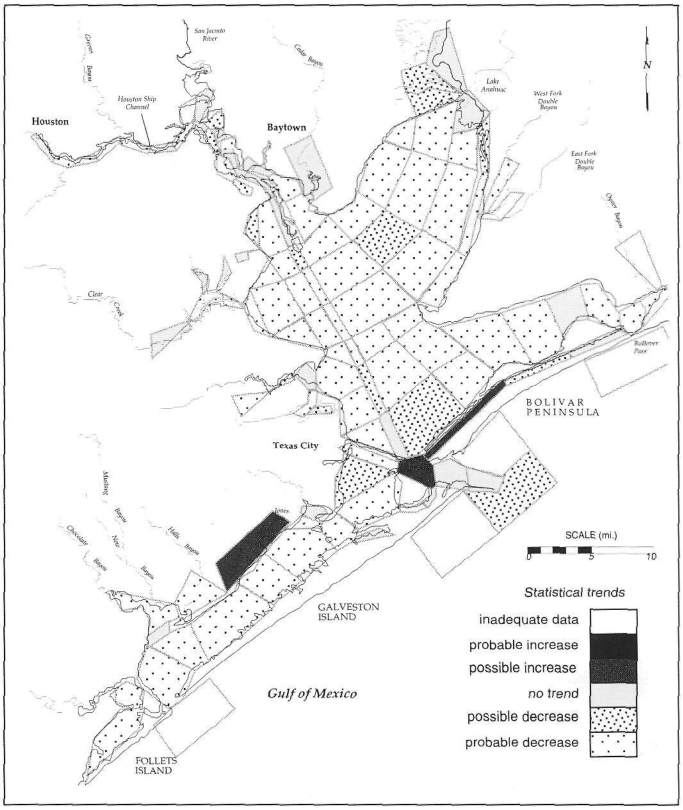
> Salinity has declined about 0.1-0.2 ppt per year over the three-decade period of record.
>
> Water temperature, especially in the summer, has declined at a nominal rate of 0.05°C/yr.
>
> Dissolved oxygen is generally high throughout Galveston Bay, averaging near saturation over extensive areas. Exceptions to this are in poorly flushed tributaries that receive runoff and waste discharges.
>
> Total suspended solids have declined throughout the system to levels roughly one-third of those 25 years ago.
>
> Declines in nitrogen and phosphorus concentrations throughout the bay have occurred over the past two decades, total ammonia nitrogen on the order of 0.1 mg/L/yr; total nitrate on the order of 0.01 mg/L/yr; and total phosphorus on the order of 0.05 mg/L/yr.
>
> Total organic carbon has declined to about one-third of its concentration in the mid-1970s, and chlorophyll-*a* to about one-half the level of a decade ago.
>
> Most metals in water and sediment have declined, particularly in areas of maximal concentrations, (the upper Houston Ship Channel), where the rates of decline per decade for sediment concentrations of chromium, mercury and zinc are a factor of two, copper and nickel a factor of three, and arsenic, cadmium and lead a factor of ten.
>
> Fecal coliform bacteria levels have generally declined over much of the bay due to improved/increased sewage treatment. Exceptions to this trend occur in a few isolated areas in West Bay, and the western urbanized tributaries of the bay system retain high bacterial levels.

In summary, the geographical problem areas of Galveston Bay are in regions of intense human activity, including urban areas, points of surface runoff, waste discharges, and shipping. The quality of the bay is generally good, and where it is degraded there is a general trend of improvement, in many cases substantial (see FIGURE 6.12 for summary of trends in the upper Houston Ship Channel).



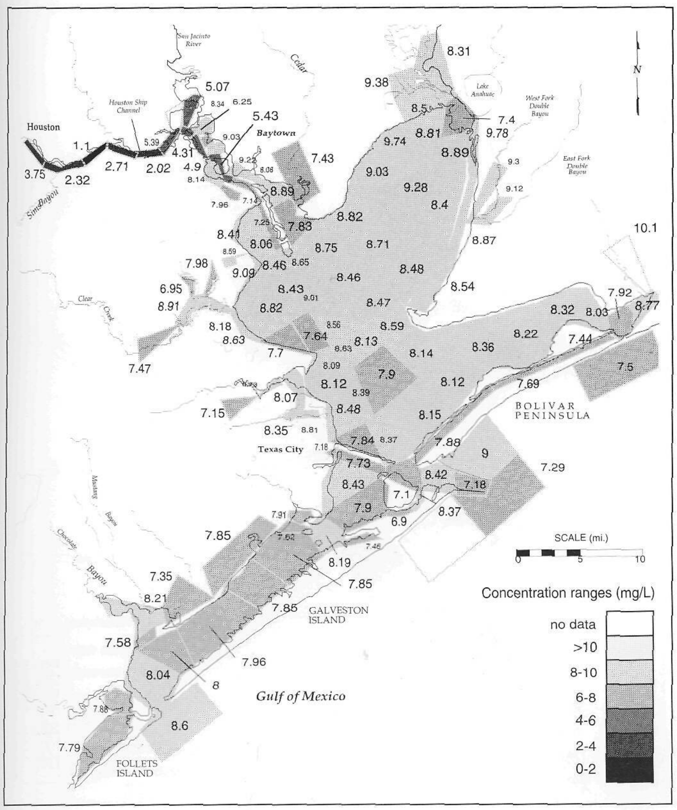
Source: Ward and Armstrong, 1992

FIGURE 6.4a. *Average concentration of total suspended solids in Galveston Bay, 1950-1990.*



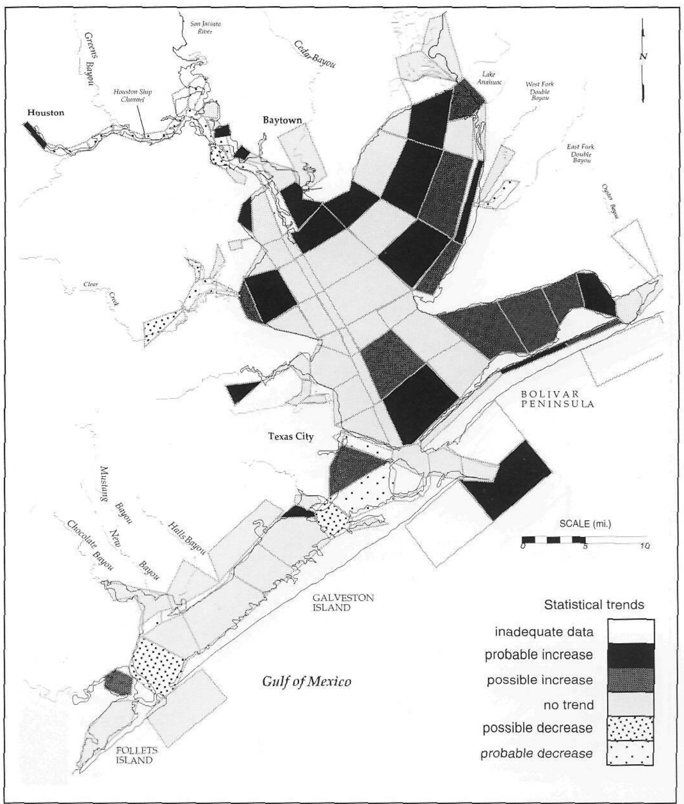
Source: Ward and Armstrong, 1992

FIGURE 6.4b. *Statistical trends for total suspended solids in Galveston Bay, 1950-1990.*



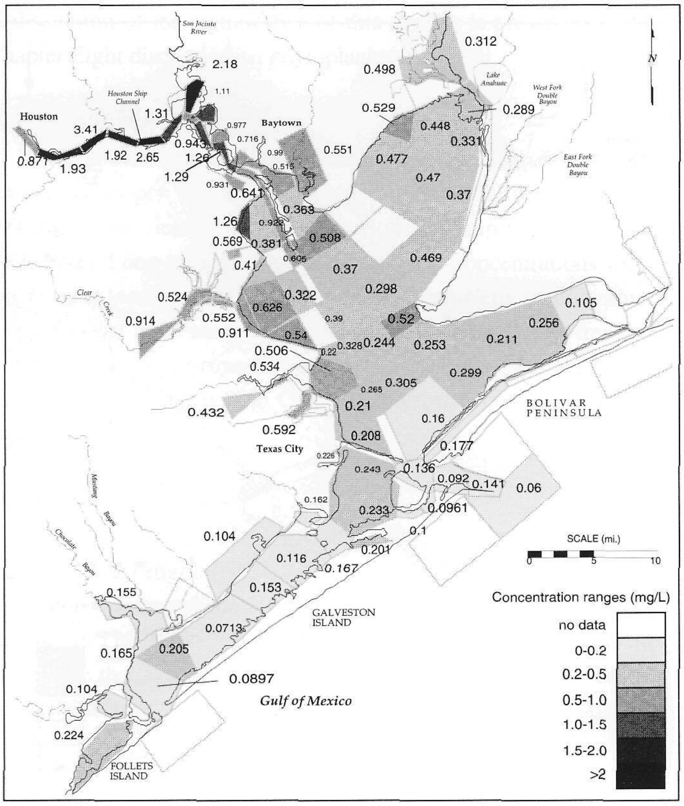
Source: Ward and Armstrong, 1992

FIGURE 6.5a. *Average concentrations of dissolved oxygen in the upper 0.5 m of Galveston Bay, 1950-1990.*



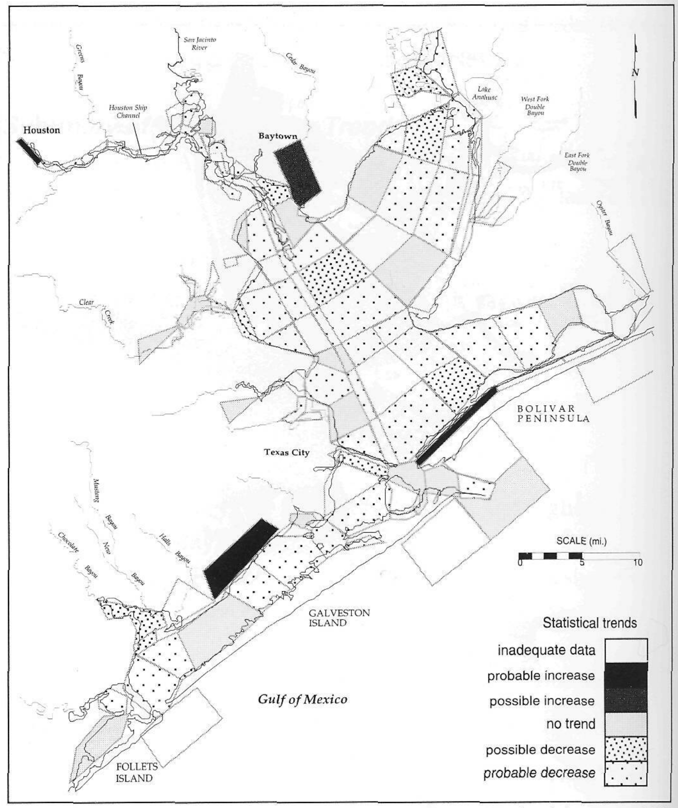
Source: Ward and Armstrong, 1992

FIGURE 6.5b. *Statistical trends for dissolved oxygen deficit in the upper 0.5 m of Galveston Bay, 1950-1990. Dissolved oxygen deficit is the difference between saturation level and the observed level.*



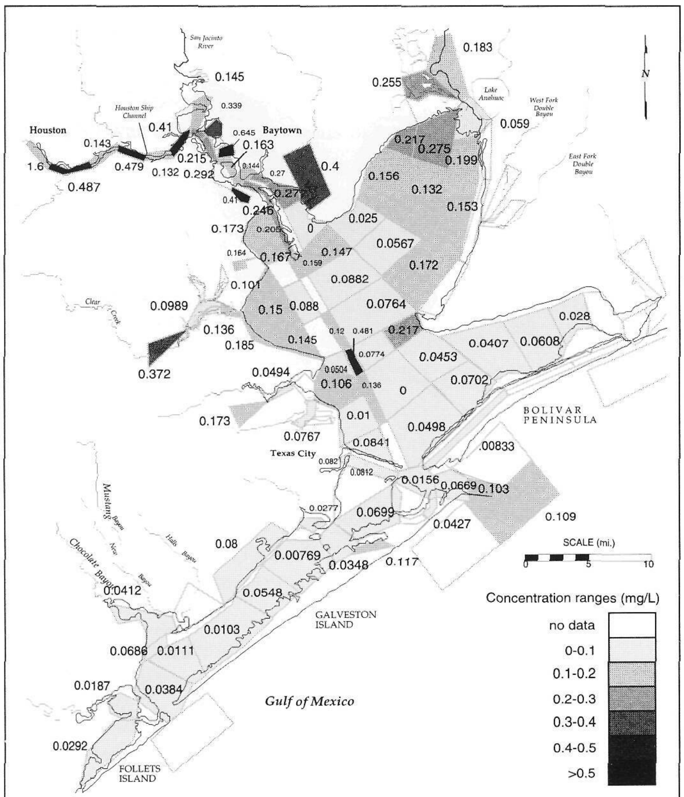
Source: Ward and Armstrong, 1992

FIGURE 6.6a. *Average concentrations of total phosphorous in water for Galveston Bay, 1967-1990.*



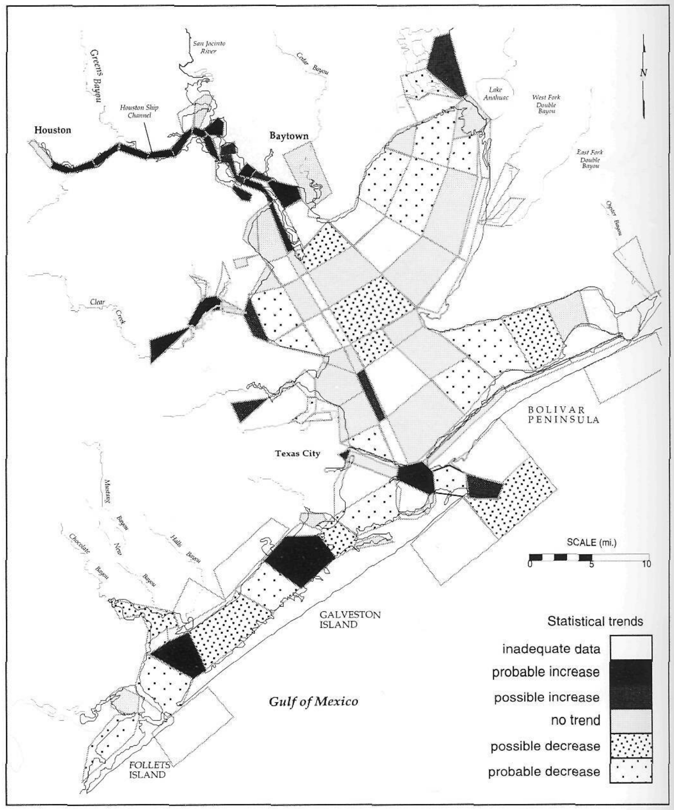
Source: Ward and Armstrong, 1992

FIGURE 6.6b. *Statistical trends for total phosphorus in water for Galveston Bay, 1967-1990.*



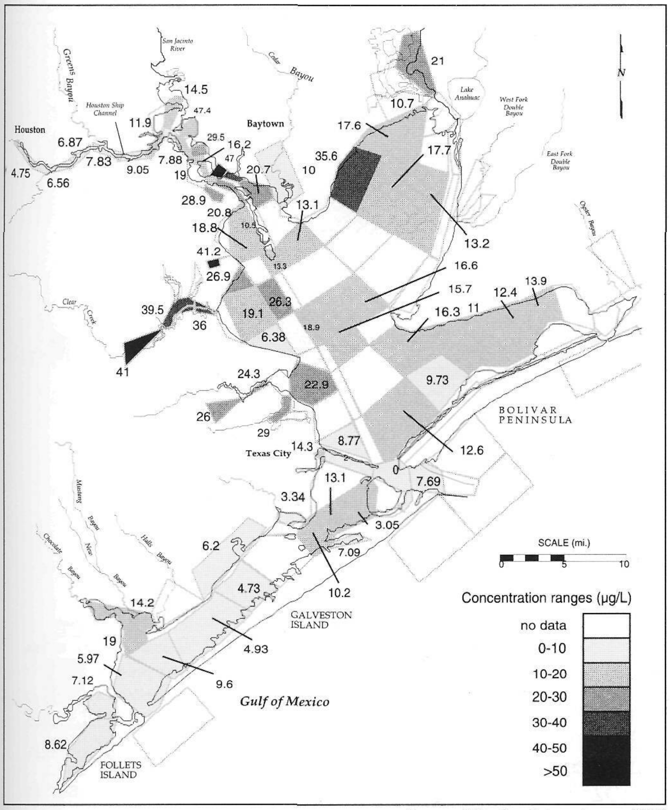
Source: Ward and Armstrong, 1992

FIGURE 6.7a. *Average concentrations of nitrate (NO_3) in water for Galveston Bay, 1967-1990.*



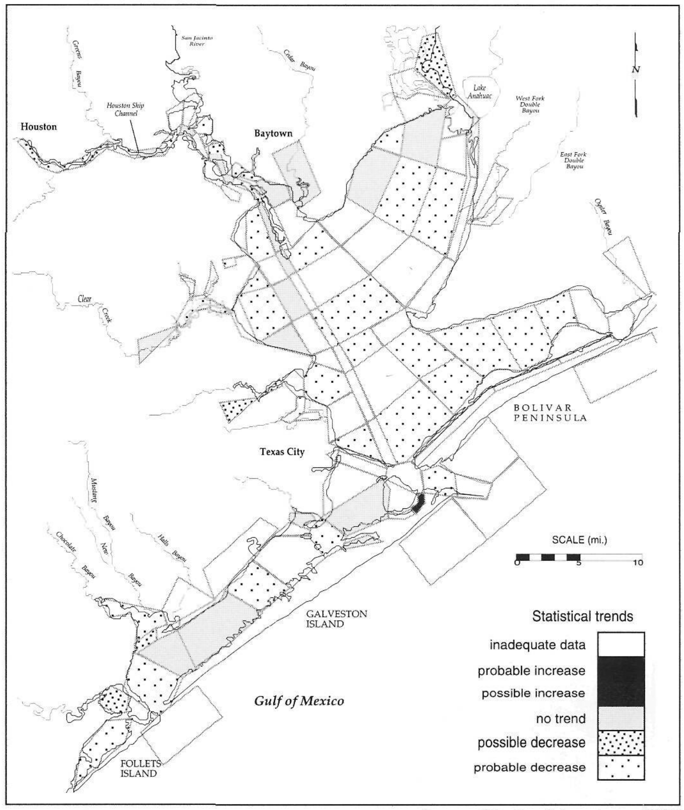
Source: Ward and Armstrong, 1992

FIGURE 6.7b. *Statistical trends for nitrate (NO_3) in water for Galveston Bay, 1967-1990.*



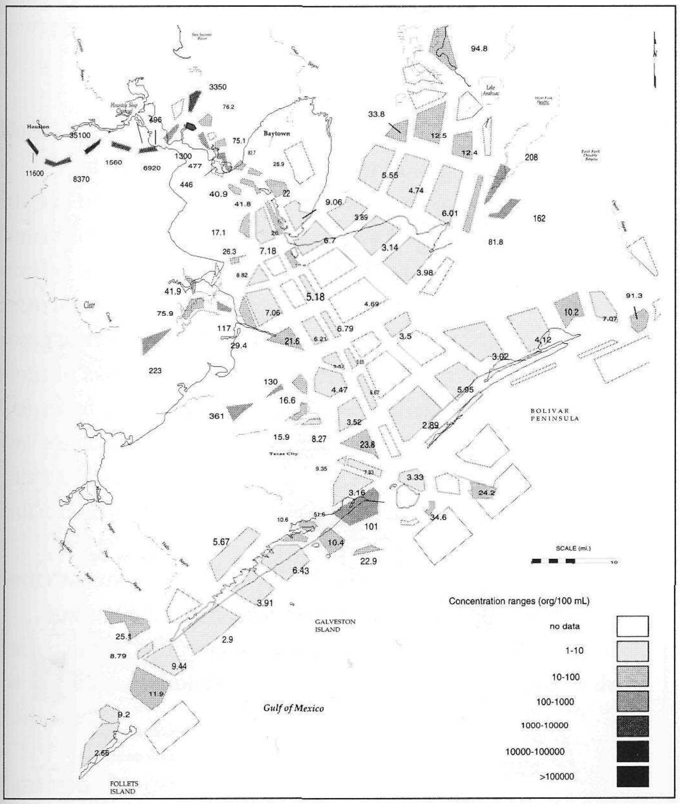
Source: Ward and Armstrong, 1992

FIGURE 6.8a. Average concentrations of chlorophyll-a in water for Galveston Bay, 1967-1990.



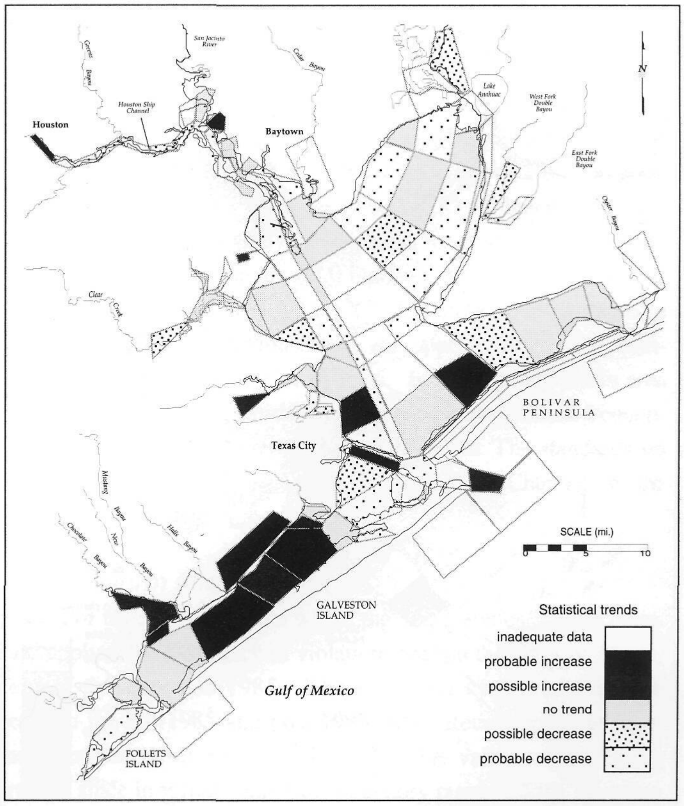
Source: Ward and Armstrong, 1992

FIGURE 6.8b. Statistical trends for chlorophyll-a in water for Galveston Bay, 1967-1990.



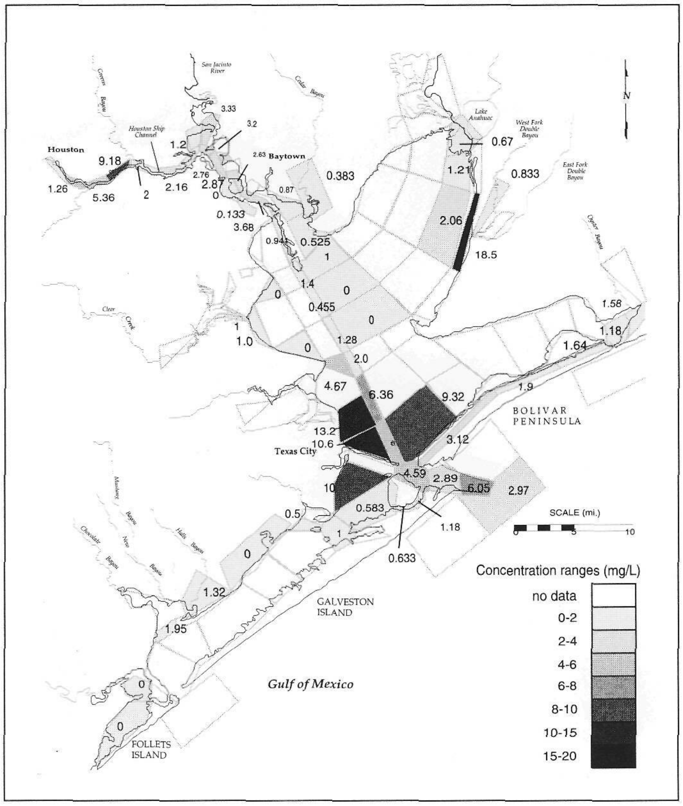
Source: Ward and Armstrong, 1992

FIGURE 6.9a. Geometric mean concentrations of fecal coliform bacteria in water for Galveston Bay, 1968-1991.



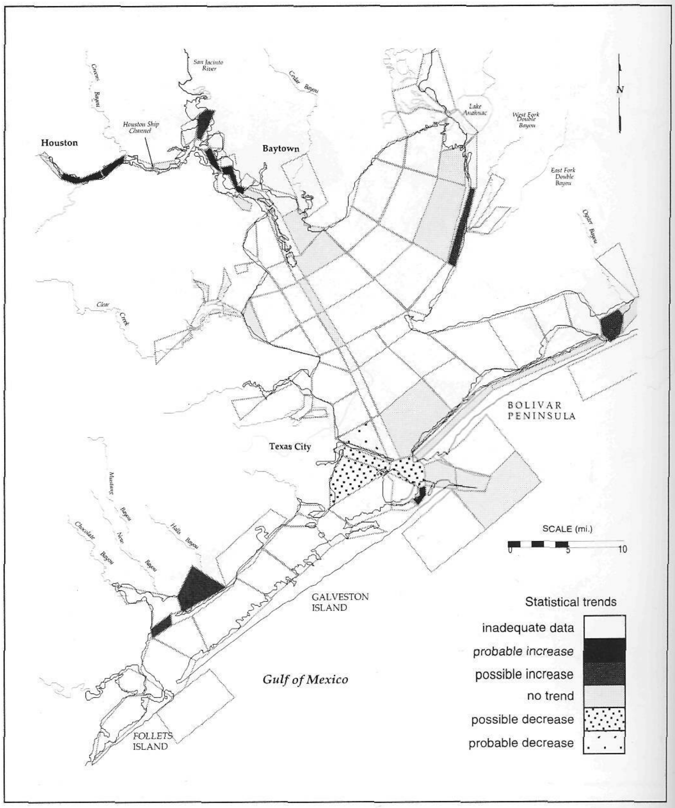
Source: Ward and Armstrong, 1992

FIGURE 6.9b. Statistical trends for fecal coliform bacteria concentrations in water for Galveston Bay, 1968-1991.



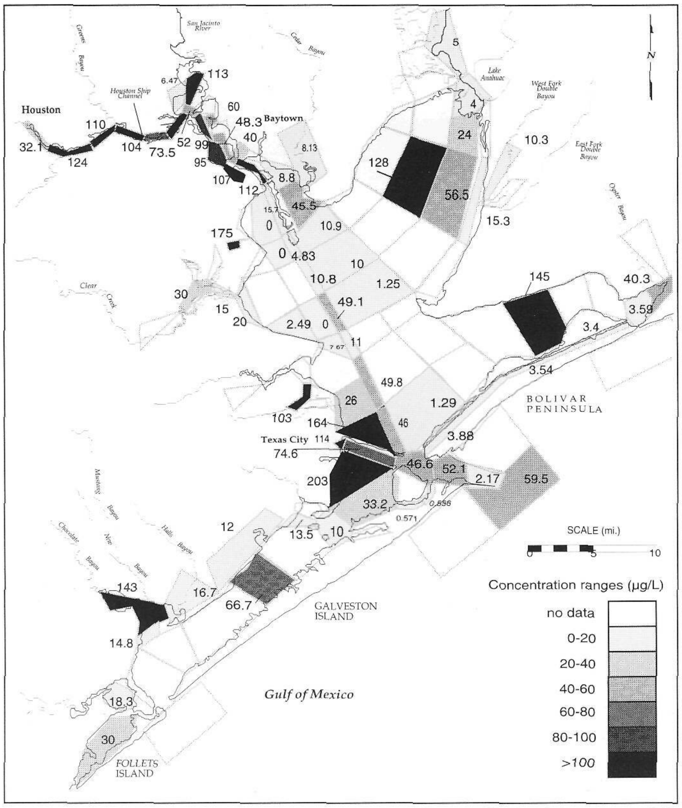
Source: Ward and Armstrong, 1992

FIGURE 6.10a. *Average concentrations of oil and grease in water for Galveston Bay, 1974-1988.*



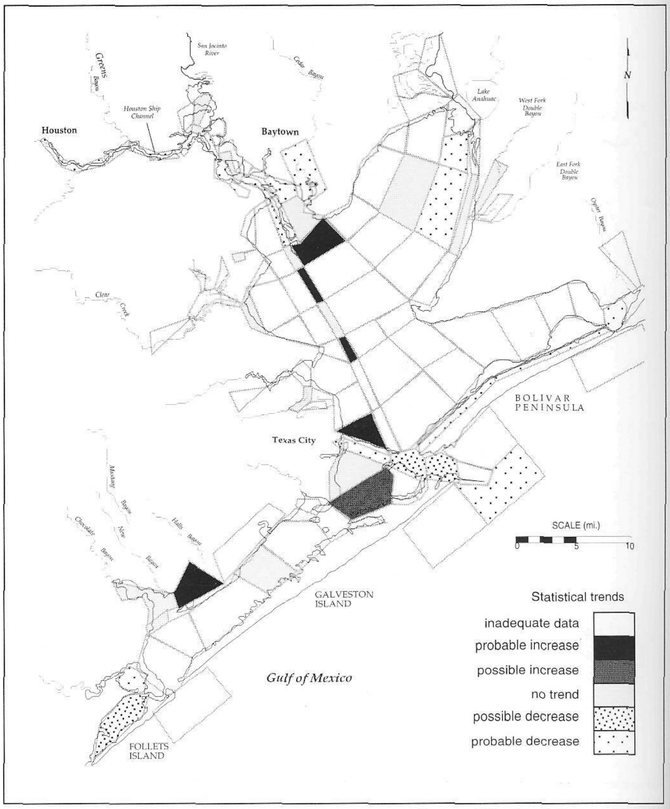
Source: Ward and Armstrong, 1992

FIGURE 6.10b. *Statistical trends for oil and grease in water for Galveston Bay, 1974-1988.*



Source: Ward and Armstrong, 1992

FIGURE 6.11a. *Average concentrations of total copper in water for Galveston Bay, 1967-1990.*



Source: Ward and Armstrong, 1992

FIGURE 6.11b. *Statistical trends for total copper in water for Galveston Bay, 1967-1990.*

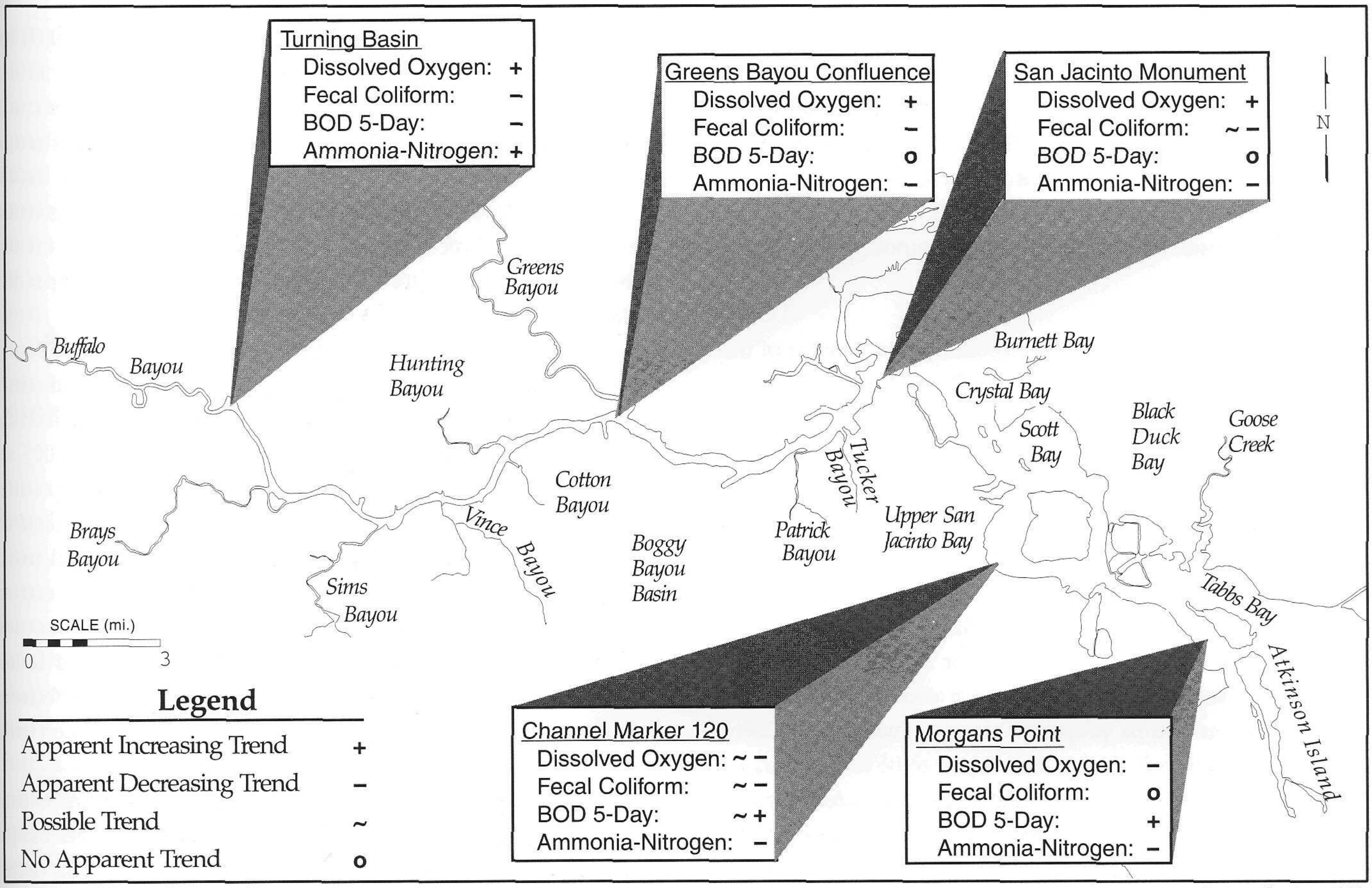


FIGURE 6.12. Water quality trends at several locations in the upper Houston Ship Channel. Period of record for the listed parameters varied, but in general corresponds to a ten to 20 year history.

Violations of State Standards and Federal Criteria

Ward and Armstrong (1992) compared the compiled bay data set to current Texas Natural Resource Conservation Commission *Surface Water Quality Standards* (which are segment-specific and legally enforceable; see TABLE 6.1) and Environmental Protection Agency water quality criteria (which are more general in nature). They tabulated the violations of these standards, and indicated that these exceedances "may be indicative of degraded water quality." The *Standards* require certain measurement protocols and frequencies to establish violations. While the historical data do not necessarily meet these requirements, standards exceedances can nevertheless indicate possible problems.

Temperature

Since 1985, there have been violations of the 95°F (35°C) standard in two segments, both in the upper Houston Ship Channel. The frequency of violation is on the order of five percent for these two segments.

Dissolved Oxygen

In the open bay and other segments with a four or five mg/L DO standard, there were scattered violations representing some two percent of the data. These violations were concentrated in areas near outflows and wastewater treatment discharges, such as Chocolate Bay and the upper Houston Ship Channel downstream of the San Jacinto Monument. The three upper Houston Ship Channel segments that experienced severe DO depletion in the past have improved significantly in violation frequency. In Segment 1005, all violations of the past 2.0 mg/L standard have been eliminated (the standard is now 4.0 mg/L). Segment 1006 experiences about a ten percent violation rate in the upper reaches now, compared to over 50 percent prior to 1985. In the Turning Basin area (Segment 1007) most locations had less than a five percent frequency of violation of the current 1.0 mg/L standard. The standards set for dissolved oxygen on the upper Houston Ship Channel are the lowest for any waters of the state.

Fecal Coliform Bacteria

For tributary segments where the 200 colonies/100 mL standard applies, the frequency of violations was on the order of 30 percent of the data pre-1985. There was no systematic change between the pre-1985 and post-1985 data. Recent coliform measurements, however, may be biased to higher values as a sampling artifact, since in recent years (for regulatory purposes) the sampling was directed more to events which would be expected to cause increases in coliforms.

Among the bay segments, the most frequent violations for

Clear Lake, the upper Houston Ship Channel, the Trinity River, Chocolate Bayou and Galveston Channel. In the upper Houston Ship Channel, where the standard is 2000 colonies per 100 mL, there was a substantive reduction in the violation rate since 1985, though recent frequencies were still on the order of 35 percent. Violation of the 14 colonies per 100 mL criterion for oyster growing waters is discussed in Chapter Nine.

Metals

Metals data are difficult to interpret because: 1) most of the data is reported as total metals while the Texas Natural Resource Conservation Commission water quality criteria are for dissolved metals (Ward and Armstrong, 1992); 2) the data are sparse; and 3) traditional sampling methods and analytical techniques for heavy metals may have greatly overestimated the actual concentrations in estuaries (Benoit and Santschi, 1991; Santschi et al., 1993). When the existing total metals data were used to compare against the dissolved metals criterion, it appears that Galveston Bay is "at the threshold of what would be satisfactory for an estuarine regime" (Ward and Armstrong, 1992). However, if dissolved metals data from ultraclean analytical programs are examined, the ambient metal concentrations in Galveston Bay appear to be lower by a factor of ten than the state's chronic aquatic life criteria for zinc and lead and one-forth of the chronic criterion for copper (Benoit and Santschi, 1991).

Pesticides and Organics

Two of 18 measurements in two Houston Ship Channel segments exceeded the Environmental Protection Agency's criterion for chronic DDT concentration, 0.001 µg/L (one part per trillion). In three of the Ship Channel segments the PCB criteria for marine and fresh water environments were violated in eight of 16 measurements. Both these compounds are now highly regulated, but their high persistence is evident in the data.

Discussion

Ward and Armstrong (1992) noted that the above-stated trends in hydrographic parameters such as salinity and temperature are unexplained. They found no clear association between the decline in salinity and the volume of fresh water inflow. Hypotheses to account for the observations involve variations in the timing of inflow events and the associated salinity response, reduced salinities in the adjacent Gulf of Mexico, or reduced intensity of interaction between estuarine and Gulf waters. Hypothetical causes for the decline in temperature include alteration in climate (e.g., air temperature, wind, cloud cover) and altered interaction with the Gulf of Mexico.

Toxic contaminants are present in the waters of Galveston Bay, but their significance is difficult to assess. One tool utilized to assess toxicity is **toxicity testing**, in which live laboratory organisms are exposed to samples of bay water using standardized methodologies. Crocker (1991) conducted a water quality and ambient toxicity investigation of the upper Houston Ship Channel and San Jacinto River (Segments 1001, 1005, 1006 and 1007) and three tidal tributaries (Brays, Greens, and Sims Bayous). Results showed no significant chronic toxicity effects to sea urchins or sheepshead minnows. However, some toxicity was evident in algal and mysid shrimp tests. The recurring pattern of ambient toxicity indicated that water quality was variable and that the potential exists for impairment of the aquatic life use designated for segments 1001 (San Jacinto River Tidal) and 1005 (in the upper Ship Channel).

In the Environmental Protection Agency Ship Channel Study, water quality was observed to exceed standards and criteria for several parameters (Crocker, 1991). During warm weather, dissolved oxygen standards were not achieved in Segment 1005 and Segments 1006 and 1007 had pronounced **hypoxia** (low dissolved oxygen). Chemical-specific criteria exceedances were noted for ammonia, arsenic, copper, cyanide, lead, manganese, nickel, selenium, and total residual chlorine. However, these metals data are subject to the same limitations previously noted because they were not collected and analyzed using ultraclean techniques, and the analytical method used was subject to positive salinity interferences. Several organic priority pollutants were detected at low concentrations.

An overall trend of interest is the systematic decline in nutrients, suspended solids, and chlorophyll-*a* in the bay over the past several decades (Ward and Armstrong, 1992). The TSS decline may have resulted from a general pollutant load reduction due to a combination of advanced waste treatment, entrapment within reservoirs, and changing land use. There is some evidence that suspended solids from urban watersheds (such as Brays Bayou) have declined as construction activity has dwindled over the past 15 years in Houston. Nitrogen, and particularly phosphorus, have an affinity for fine-grain particulates (TSS), so their declines may be due to the same causes, although some of the decline in nitrogen concentrations could also be attributed to more stringent regulation of discharges.

Biologically, the nutrient declines appear to have led to associated declines in chlorophyll-*a* (Chapter Eight) and organic carbon due to reduced phytoplankton biomass. This may also be causing a slight increase in the dissolved oxygen deficit in parts of the bay (see FIGURE 6.5b). The optimal level of nutrients and primary productivity in Galveston Bay is a topic of ongoing debate. The trends may reflect desirable water quality improvements, or they may signal a warning that the base of the food chain, if trends continue, may be jeopardized. In either case, future monitoring of the involved parameters is crucial.

Several recommendations by Ward and Armstrong (1992) addressed data collection and management problems which have traditionally constrained bay managers. A need exists to recognize data collection as a collective enterprise among the various agencies, with improved altruism among scientists working in the estuary. Continuity of data in time and space, for a long period of record, are necessary for a basic understanding of the complex dynamics in the system; this need implies stable funding. The diverse mandates of the agencies involved will always translate to differing data collection programs, but the potential for coordination of these programs is great. For example, the cost of putting a sampling crew on a specific station far outweighs the relatively small incremental cost of acquiring additional measurements for use by other agencies or investigators. Currently, the various data collection programs contribute to no overall bay monitoring goals or information syntheses; bay-wide studies currently require prodigious efforts to retrieve information sets individually from diverse agency sources.

SEDIMENT QUALITY

Estuarine sediments are a significant aspect of the overall environmental quality of Galveston Bay. Many materials introduced originally in a water phase have an affinity for sediment particles, for example phosphorus compounds and many organic toxicants. An equilibrium is established between the water and sediment concentrations of various compounds–an equilibrium that can be altered by both natural and human disturbances of the system. Sediments are an environmental sink (storage compartment) for many contaminants, and because sediments are also a biological habitat, food web uptake of toxicants can be influenced by sediment concentrations of these contaminants. Frequently, contaminants can be detected in analytical or toxicity testing of sediments, but neither type of test detects these contaminants or their effects in overlying water from the same location. Overall, the role of sediments in the fate and effects of environmental contaminants is complex, dynamic, and incompletely understood.

The analysis by Ward and Armstrong described above for water quality was also applied to existing sediment data. The sediment analyses, however, were hampered by sparse data and a predominance of measurements below analytical detection limits. The concentration ranges reported are representative only of the collected samples and may not be representative of the entire bay, due to the fact that large areas of the bay remain unsampled. Likewise, the data scarcity imposed statistical limitations on the trend analyses, making any trends (even if they actually exist) difficult to identify. Sediment findings are summarized in FIGURES 6.13–6.15, which follow the same rationale as for water quality parameters, and for which concentrations below the detection limit were assigned a value of zero.

Sediment Quality Status and Trends

In Galveston Bay sediments, metals and commonly measured organic compounds (such as total phosphorus, oil and grease, Kjeldahl nitrogen, and volatile solids) appear to follow the same general spatial distribution as most of the water quality parameters. Elevated concentrations occur in regions of runoff, inflow and waste discharges, and lower, more-or-less uniform concentrations in the open bay, with the Houston Ship Channel generally the focus of maximal concentrations in the system (Ward and Armstrong, 1992). Specific findings are given below.

Total Phosphorus

Total Phosphorus concentrations for the few segments that were sampled ranged from below 200 mg/kg to greater than 1000 mg/kg in the upper Houston Ship Channel. Sediment phosphorus content is not always meaningful for silts, clays, and muds, which tend to have generally high absorbed phosphorus. There were virtually no phosphorus data for sediments from open bay segments.

DDT

DDT concentrations in the bay ranged from less than one µg/kg to more than 30 µg/kg (FIGURE 6.13). The highest DDT levels were in the upper Houston Ship Channel and near other points of inflow (Cedar Bayou, Clear Creek and the Trinity River). Two segments in the upper Houston Ship Channel were noteworthy for their elevated DDT concentrations of 154 and 467 µg/kg. For this parameter, data were inadequate for a meaningful trends analysis.

Oil & Grease

Oil & Grease concentrations ranged from less than 1,000 mg/kg to greater than 5,000 mg/kg in the upper Houston Ship Channel. Only five segments within the bay itself had oil and grease concentrations which exceeded 2,000 mg/kg: one segment in Trinity Bay, two segments near Clear Lake, one segment near the Texas City Dike, and one segment near Chocolate Bayou (FIGURES 6.14a and 6.14b).

Metals

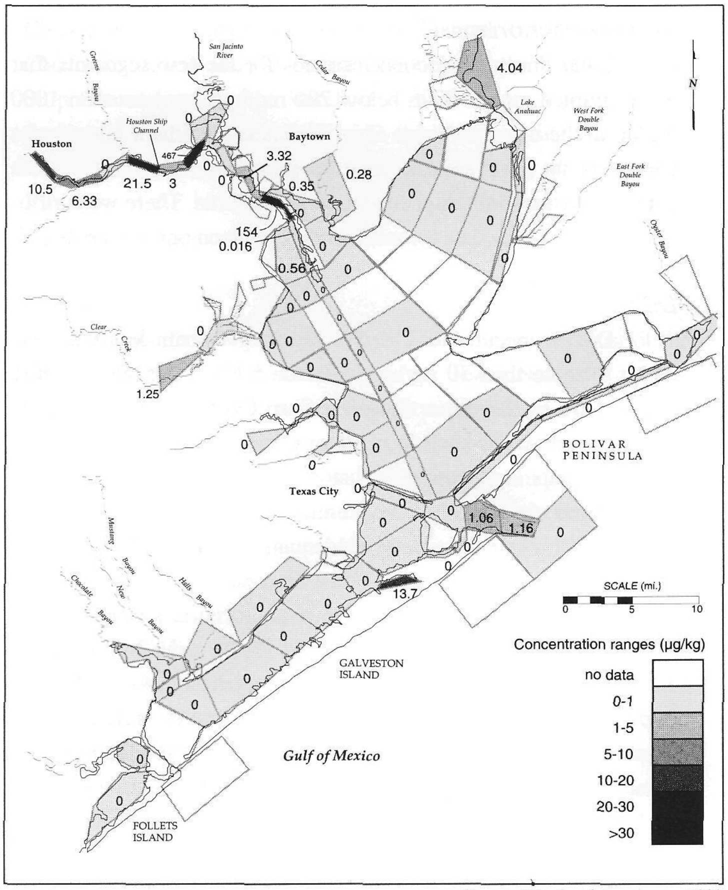
Copper concentrations ranged from below ten µg/kg to greater than 50 µg/kg. The higher concentrations (greater than 30 µg/kg) were associated with the upper Houston Ship Channel, Trinity Bay, Clear Lake, and the Texas City Dike (FIGURES 6.15a and 6.15b). Zinc concentrations ranged from less than 50 µg/kg to greater than 250 µg/kg, with highest concentrations in the upper Houston Ship Channel and Trinity Bay. Other mean concentrations included: mercury–0.005 to 0.5 µg/kg; lead–ten to 50 µg/kg; and chromium–20 to 100 µg/kg.

PCBs

Approximately ten percent of the bay has been sampled for PCBs, yielding an average sediment concentration of 76.8 µg/kg (282 samples, for which 233 samples below the analytical detection limit were assigned a concentration of 0). By using this average over an area equivalent to ten percent of the bay's area and applying a range equal to two orders of magnitude to account for uncertainty, a preliminary estimated range for the total weight of PCBs in bay sediments is between 830 and 83,000 kgs.

Summary of Sediment Status and Trends

Highest metals concentrations were found in upper Houston Ship Channel sediments. Clear Lake and, to a lesser extent, Dickinson Bayou sediments also contained elevated concentrations, especially arsenic, copper and mercury. Sediments in the vicinity



Source: Ward and Armstrong, 1992

FIGURE 6.13. Average sediment concentrations of DDT in Galveston Bay, 1971-1990. Data were inadequate for a meaningful trend analysis.

of the Trinity River in upper Trinity Bay contained relatively low concentrations of metals. Chromium and lead were generally elevated in sediments throughout Galveston Bay, relative to data compiled in Moore and Ramamoorthy (1984) typifying natural aquatic systems. Arsenic, cadmium, mercury, copper, zinc, and nickel were generally low in the open bay.

Excepting arsenic, trends for the metals are generally downward. This is especially true in the upper Houston Ship Channel where arsenic is also declining. In the channel, the rates of decline over a decade are sufficient to reduce sediment concentrations of chromium, mercury and zinc by a factor of two; copper and nickel by a factor of three; and arsenic, cadmium and lead by a factor of ten (Ward and Armstrong, 1992). One notable exception to this general improvement is the segment just north of the Texas City Dike, which shows increasing trends in arsenic, chromium, lead, nickel and zinc.

In a recent EPA study (Crocker, 1991), Houston Ship Channel bottom sediments were relatively nontoxic to test amphipods and sheepshead minnows, excepting three sampling stations. Environmental Protection Agency priority pollutants were not detected in sediments, but a variety of metals and organic priority pollutants were detected in edible fish and crab tissue at concentrations below levels of concern.

Sediments may constitute a long-term continuing source of PCBs and PAHs, even after sources are reduced or removed. Manufacture of PCBs in the U.S. was banned by the Toxic Substances Control Act of 1976, but certain existing uses of PCBs are currently allowed under controlled conditions. PAHs may largely be associated with combustion products and urban oil and grease (crankcase oil) and tend to be associated with sediments. Atmospheric deposition and precipitation of such pollutants as PCBs, mercury, and PAHs to Galveston Bay requires further study, but are increasingly being recognized as significant in other parts of the country.

Recent data collected by Carr (1993) from 24 sites around the bay yielded additional information about the sediment quality in Galveston Bay. The concentration of chlorinated hydrocarbons, for example, was below the detection limit (0.01 µg/g) for most of the samples except a few stations with detectable concentrations of PCBs. The concentration of the pesticides Aldrin, Dieldrin, Endrin and Mirex were below detection limits for all stations. PAHs were elevated at a number of sites; specifically at three sites adjacent to produced water separator platforms. Additional results from the Carr study are presented below and in FIGURE 6.16.

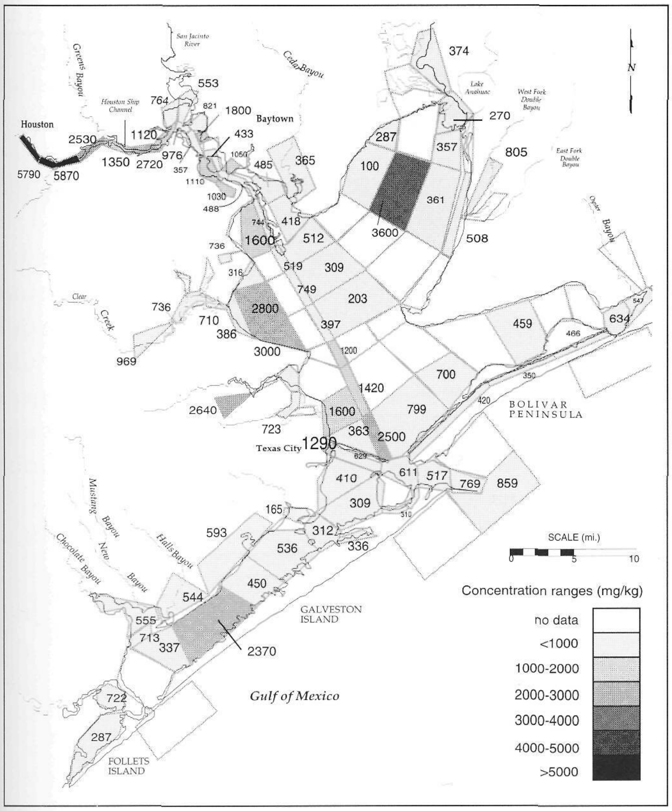
Sediment Toxicity

Analytical findings of the sort presented above provide good information about the presence and concentrations of contaminants in sediments, but shed little light on their effects in the ecosystem. Important questions relate to the toxicity of contaminants to organisms utilizing sediments, and the resulting implications for biological community structure. Ultimately, food chain concentration of sediment contaminants can affect humans through consumption of seafood taken from the estuary.

To address some aspects of sediment toxicity, Carr (1993) conducted a sediment quality triad study of Galveston Bay. The triad approach involves collection of three different sorts of data from each location, producing amore comprehensive description of toxic contamination than any measurement alone. The three types of measurements utilized were: 1) chemical analysis for specific contaminant concentrations in sediment; 2) toxicity testing of sediments and sediment pore water using standard living laboratory organisms; and 3) abundance and diversity of the natural bottom-dwelling community.

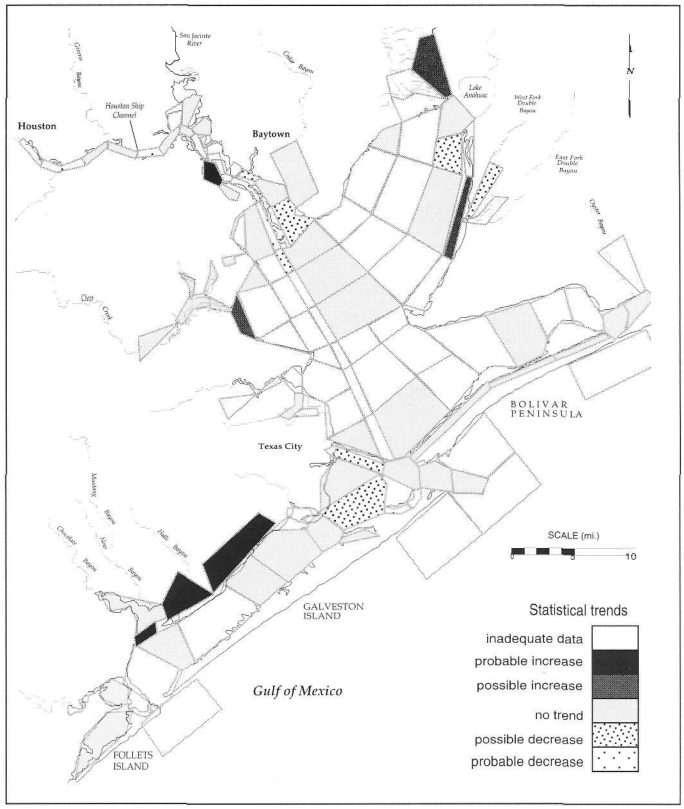
In the study, sediments were analyzed for trace metals, PAHs, chlorinated hydrocarbons, total organic carbon (TOC), and acid volatile sulfides. Two different toxicity tests were employed: 1) an American Society for Testing Materials (ASTM) method, in which a benthic amphipod was exposed to actual sediments (solid phase) to determine toxic effects; and 2) a method exposing sea urchin gametes to sediment porewater to determine toxic effects. To determine benthic community structure, organisms were identified and counted from core samples using standard benthic techniques.

The two types of sediment toxicity test yielded contradictory results. The ASTM method showed no toxicity at any station, while the porewater/sea urchin test showed significant toxicity for



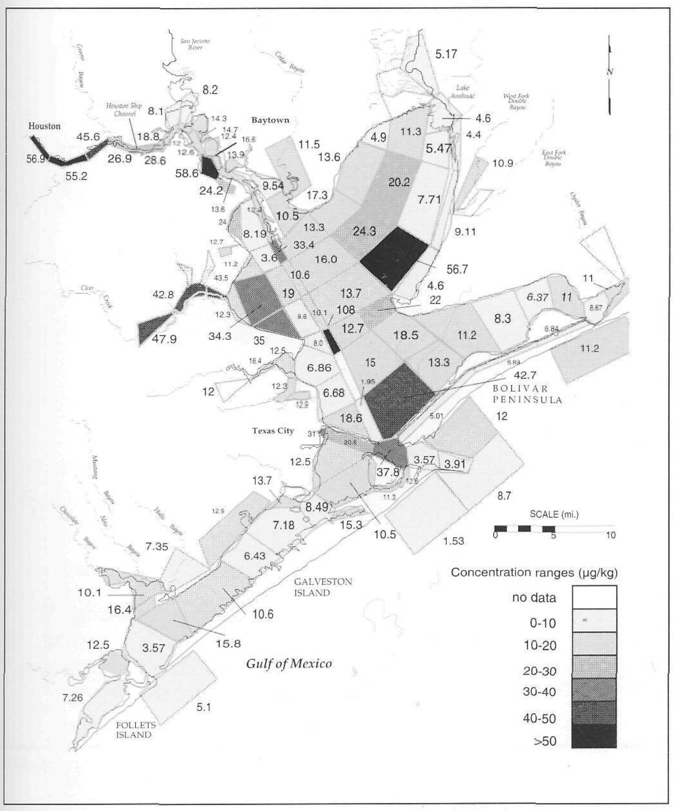
Source: Ward and Armstrong, 1992

FIGURE 6.14a. *Average sediment concentrations of oil and grease in Galveston Bay, 1972-1988.*



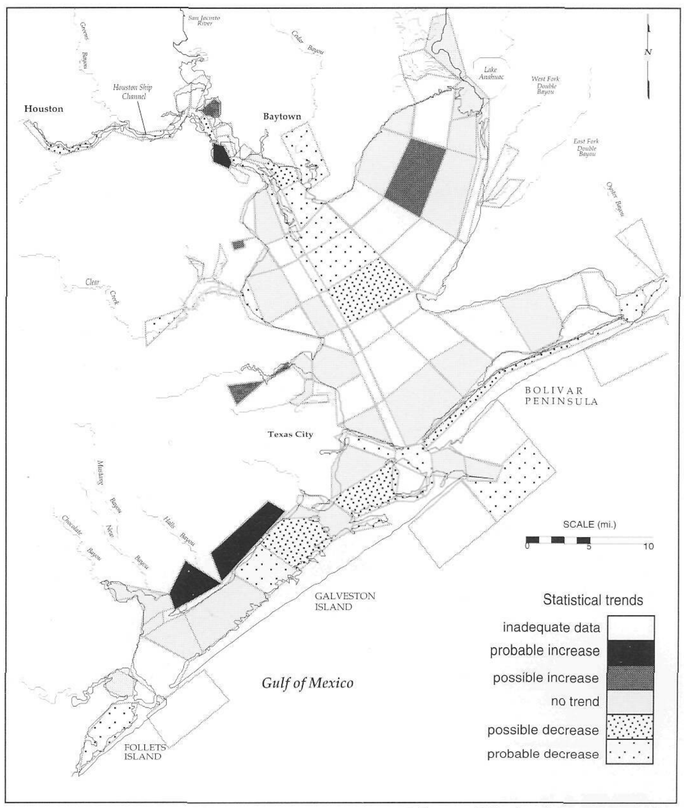
Source: Ward and Armstrong, 1992

FIGURE 6.14b. *Statistical trends for sediment concentrations of oil and grease in Galveston Bay, 1972-1988.*



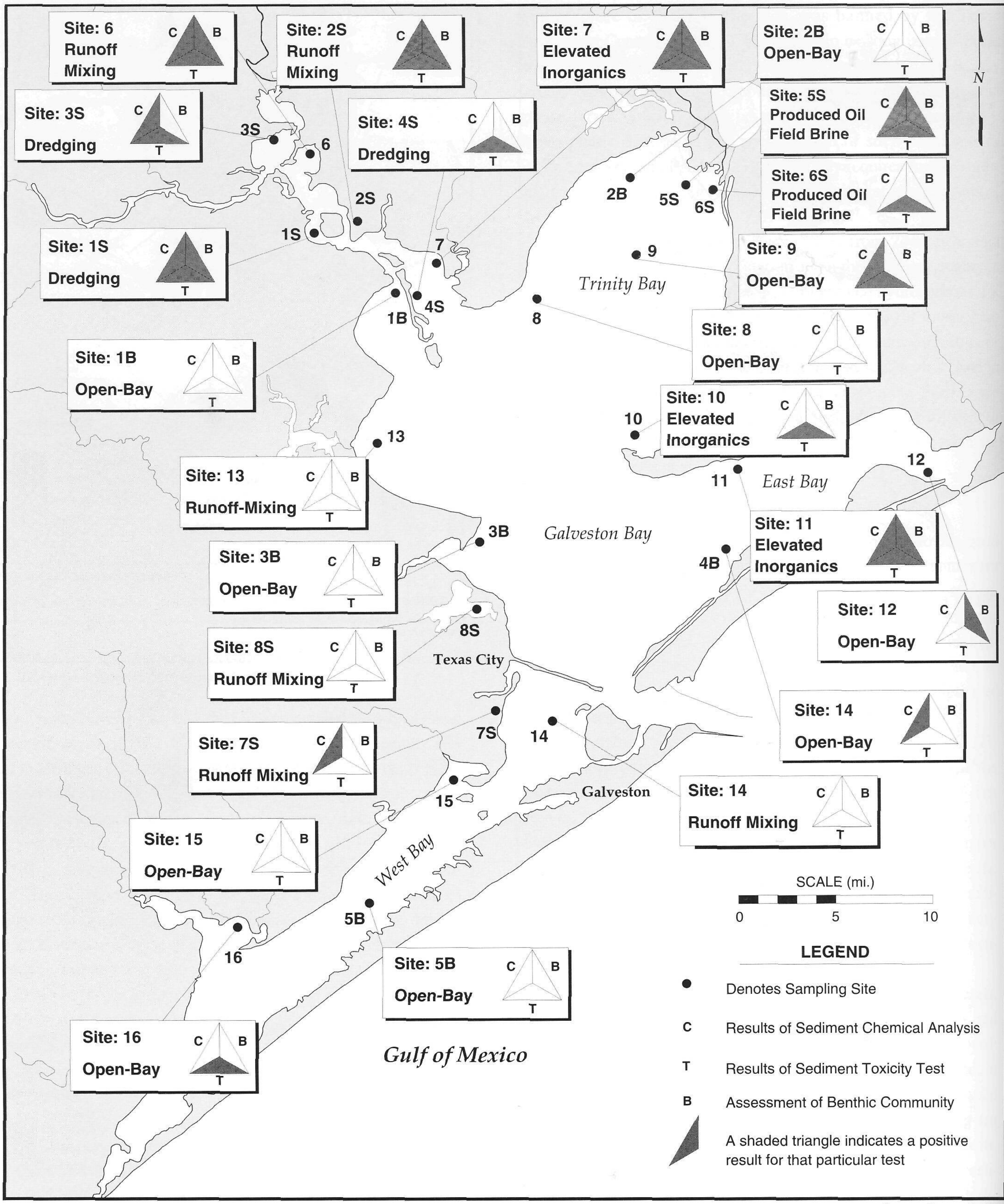
Source: Ward and Armstrong, 1992

FIGURE 6.15a. *Average sediment concentrations of total copper in Galveston Bay, 1967-1990.*



Source: Ward and Armstrong, 1992

FIGURE 6.15b. *Statistical trends for sediment concentrations of total copper in Galveston Bay, 1967-1990.*



Source: Carr et al., 1993

FIGURE 6.16. Results of the Galveston Bay National Estuary Program Sediment Quality Triad Study. In the triad approach, chemical analysis of sediments, laboratory toxicity tests with live organisms, and the composition of the natural bottom-dwelling community give a comprehensive view of contamination. Most contamination was associated with known human activities, and was generally concentrated in the upper estuary.

12 of the 24 sites. Using the more sensitive porewater/sea urchin testing method, all of five sites associated with dredge disposal of sediments showed toxicity, while only two of six sites associated with either urban or industrial runoff showed toxicity (FIGURE 6.16). Results also indicated sites sampled in the upper Houston Ship Channel were all highly degraded.

Sites adjacent to produced water separator discharges had high PAH concentrations and were highly toxic (see also the discussion of oilfield produced water in the point source section of this chapter). While the impact of these discharges decreased with distance from the outfall, the impact of chronic produced water discharges in shallow estuaries, such as Trinity Bay, was evident for some time after the discharge was discontinued, due to the accumulation and persistence of high molecular weight PAHs in sediments.

The study concluded that large expanses of bay bottom were in good condition. However, the presence of locations impacted from the specific industrial, petroleum, and dredging activities noted suggests the need for improved management of these activities.

Contaminant Potential of Dredged Material

Medina (1993) reported on the contaminant potential from the disposal of dredged maintenance material from the proposed project to widen and deepen the Houston Ship Channel. Samples were collected every 1000 feet along the entire 50-mi length of the channel, and were analyzed for chemical composition and grain size distribution. Every five stations were composited and analyzed for priority pollutants, while selected stations were analyzed for dioxin, a known contaminant north of Morgans Point. Toxicity tests and bioaccumulation analyses were also performed using Corps of Engineers/EPA guidance for testing dredged material.

For the priority pollutants, metals concentrations were within

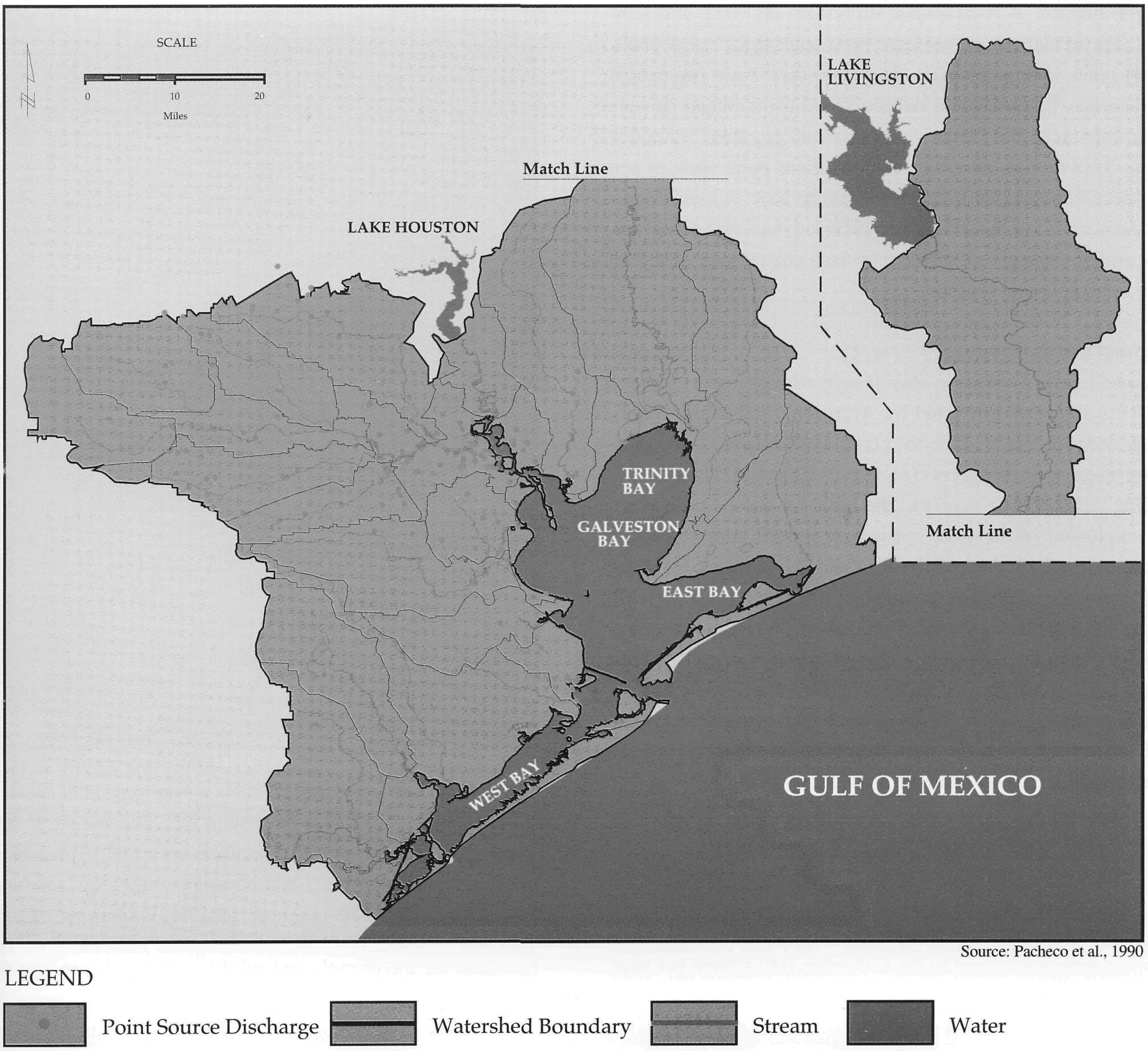


FIGURE 6.17. Major point source dischargers in the lower Galveston Bay watershed. Major dischargers are those which discharge more than one million gallons of wastewater per day; numerous other smaller point source discharges are not shown. Galveston Bay ultimately receives about 60 percent of the state's discharge wastewater.

the range of historical data (which may include excessive concentrations), while organics were generally below detection levels. Dioxin was detected in one sample in very low concentrations. Water column toxicity tests from the open bay generally indicated little or no differences in organism survival between test and reference (control) sites.

An Interagency Coordinating Team (including representatives from the Corps of Engineers, Environmental Protection Agency, U.S. Fish and Wildlife, Texas Parks and Wildlife, and the Texas Natural Resource Conservation Commission) determined that "there are no contaminant concerns related to the dredging and disposal of maintenance material" from the proposed project (Medina, 1993). The group also concluded that there were no dioxin concerns with the dredged material.

HUMAN IMPACTS: POINT SOURCE DISCHARGES

The impacts of point source discharges on water and sediment quality in Galveston Bay have been studied for many years. Principal point sources include: permitted discharges (municipal and industrial), bypasses and overflows from municipal sewage systems, unpermitted or illegal discharges, and produced water discharges. This section describes each of these point sources and their respective impact on water quality in the bay. A brief discussion of fecal coliform bacteria is also included; bacterial concentrations in estuarine waters are affected by each point source identified (as well as by nonpoint sources).

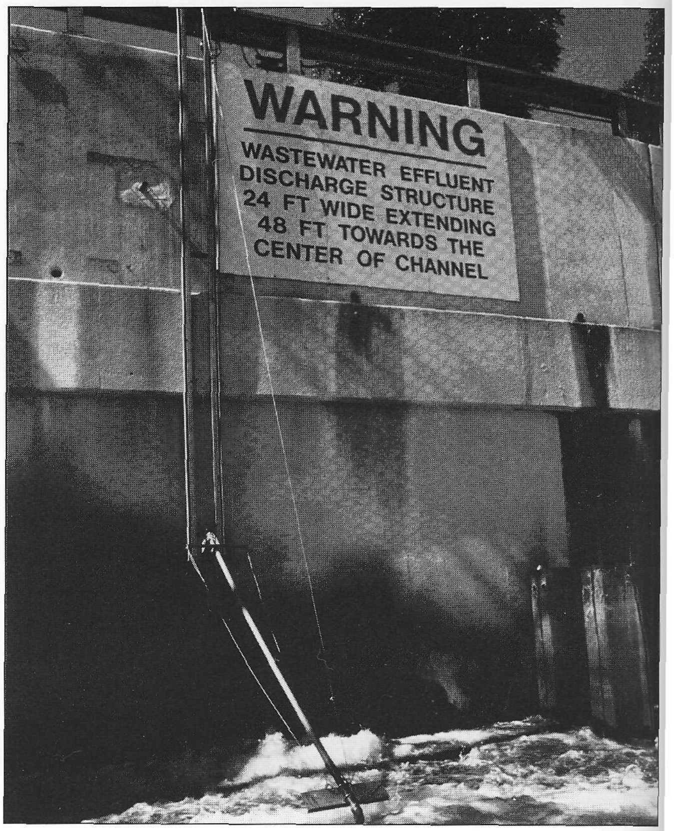
Permitted Discharges

Loadings to Galveston Bay from permitted point sources (FIGURE 6.17) were estimated by Armstrong and Ward (1994). Most discharge permits require the permittees to report their releases of some selected constituents (such as BOD and pH) in the effluent. This self-reporting data was the basis for most loading estimates calculated in the study. Because not all parameters are reported, particularly for smaller discharges, estimates for some constituents were made after the method of Pacheco et al. (1990), based on the expected effluent composition ("typical concentrations") for particular industries. This approach was used to estimate most of the loadings for the heavy metals and specific organic pollutants discussed below. In other cases (for example municipal wastes and rivers) estimates were based on correlations between reported constituent concentrations and flow.

Conventional Parameters

Annual loading estimates of each constituent reported in the 1990 self-reporting data are given in TABLE 6.2 (Armstrong and Ward, 1994). Over 1.356 trillion gallons (4,161,000 ac-ft) of wastewater were discharged to the Galveston Bay system per year, with 75 percent of this discharge from the cooling water from the Houston Lighting and Power plants located near Clear Lake, Trinity Bay, and mid-Galveston Bay. Pacheco et al., (1990) estimated that the overall "process" flow (total discharges with cooling water excluded) was 224 billion gallons per year, with the industrial and municipal components being 49 and 174 billion gallons per year, respectively. Armstrong and Ward (1994) estimated that the overall municipal wastewater discharge rate in 1990 was 135 billion gallons per year.

Biochemical and chemical oxygen demand loadings from permitted point sources amount to over 4.5 and 6.2 million kg/yr, respectively, with most of that going into the Houston Ship Channel/San Jacinto River. Total organic carbon, total suspended solids, and oil and grease follow similar patterns. Nitrogen and phosphorus are not all reported by these dischargers, making these nutrient loadings difficult to evaluate. From the limited data, ammonia appears to be the dominant form of nitrogen discharged. The reported quantities of phosphorus discharged are almost certain to underestimate the actual amounts discharged. No residual or free available chlorine or total dissolved solids loadings were reported.



Source: Texas Sea Grant College Program

The nation's third largest city produces a huge volume of treated wastewater. Here, the City of Houston's 69th Street Plant discharges to Buffalo Bayou in the upper bay system.

Priority Pollutants

Priority pollutants data were grouped by type of compound. Loadings for the phenols and substituted phenols are reported primarily as total phenols although several other forms are permitted. Some 2,800 kg/yr of total phenols (a derived estimate) were discharged to the bay, primarily into the Houston Ship Channel. Only two organonitrogen compounds had reported discharge data, and the amounts reported totaled 29 kg/yr into Segment 901. Minimal

TABLE 6.2. Constituent Loadings From Point Sources to the Galveston Bay System in 1990.

Segment[1]	Flow (Million Gallons/yr)	BOD5 (kg/yr)	Chemical Oxygen Demand (kg/yr)	Total Organic Carbon (kg/yr)	Total Kjeldahl Nitrogen (kg/yr)	Ammonia Nitrogen (kg/yr)	Phosphate Phosphorus (kg/yr)	Total Suspended Solids (kg/yr)
0801 - Trinity River Tidal	825	17,151				5,847		47,024
0802 - Trinity River below Lake Livingston	467	18,656						73,596
0901 - Cedar Bayou Tidal	3,845	58,579	272,412	14,991		37,290		108,968
0902 - Cedar Bayou Above Tidal	386	8,381	44,107					21,970
1001 - San Jacinto River Tidal	19,111	89,788	1,092,097		13,512	16,970		198,501
1005 - HSC/ San Jacinto River	7,778	631,097	214,303	1,018,939	401	264,089		862,787
1006[2] - HSC	67,993	911,155	3,152,204	249,009	198,058	155,791		2,080,112
1007 - HSC/ Buffalo Bayou	123,856	1,486,180	633,451	6,309,606	618,923	405,003	2,272	3,546,839
1013 - Buffalo Bayou Tidal	6,704	28,827	2,405	125	45,114	28,415		126,313
1014 - Buffalo Bayou Above Tidal	12,160	61,158	98	359	94,451	46,300	12	188,624
1101[3] - Clear Creek Tidal	3,003	12,278				10,866		28,915
1102 - Clear Creek Above Tidal	6,077	33,294				5,014	59	36,854
1103 - Dickinson Bayou Tidal	1,002	22,173		10,301		2,077		12,981
1104 - Dickinson Bayou Above Tidal	72	589				306		1,617
1105 - Bastrop Bayou Tidal	121	4,103						4,637
1107 - Chocolate Bayou Tidal	5,084	106,303	308,094	153,858				339,486
1108 - Chocolate Bayou Above Tidal	19	487						873
1113[3] - Armand Bayou Tidal	2,983	17,838				10,580		17,840
2421[2]- Upper Galveston Bay	436,928	34,173	7,913					43,607
2422[2,3] - Trinity Bay	417,649	2,714						5,145
2424 - West Bay	2,044	24,080						26,881
2425[2] - Clear Lake	117,648	927				65		1,989
2426 - Tabbs Bay	1,409	24,258	5,248		34,726	22,032		37,750
2427[2] - San Jacinto Bay	67,666	54,848	15,511	226,338	50,323	6,538	1,945	196,885
2429 - Scott Bay	106							
2430 - Burnett Bay	8	548	5,522					1,129
2431 - Moses Lake	2,758	75,788				85		97,906
2432 - Chocolate Bay	987	15,153						37,386
2436 - Barbours Cut	21				318	100		1,562
2437 - Texas City Ship Channel	7,490	454,881	484,347	333,443		61,239		848,364
2438 - Bayport Channel	5,172	164,470		696,482		23,072		400,661
2439 - Lower Galveston Bay	34,736	145,612	6,478	260,463		32,264		215,369
Discharge Totals	**1,356,108**	**4,505,489**	**6,244,190**	**9,273,915**	**1,055,825**	**1,133,941**	**4,288**	**9,612,571**

Source: Armstrong and Ward, 1994

[1]No data for East Bay, Black Duck Bay, Bastrop Bay/Oyster Lake, Christmas Bay, and Drum Bay
[2]Segments 1006, 2421, 2422, 2425, 2427 are influenced by cooling water discharges; HSC = Houston Ship Channel
[3]Segments 1101, 1113, and 2422 are subdivided, constituting a total of seven segments

amounts of the low and high molecular weight polycyclic aromatic hydrocarbons (PAHs) were reported. Of the chlorinated aromatic hydrocarbons, only chlorobenzene and 1,2-dichlorobenzene were reported to be discharged into Segment 901. No chlorinated aliphatic hydrocarbons, halogenated ethers, phthalates, or miscellaneous oxygenated compounds were reported discharged. One discharger of PCBs with an estimated discharge rate of 15.7 kg/yr of PCBs was identified in the Houston Ship Channel. It should be noted that the techniques for calculating the total loads for priority pollutants tended to overestimate discharges to the bay.

Over 1,800 kg/yr of chlorinated hydrocarbons were released by permitted point sources, mostly into the Houston Ship Channel and Cedar Bayou. Toluene was the major volatile aromatic hydrocarbon discharged, amounting to almost 37 kg/yr discharged into Segments 901 and 1107. Benzene was also released into Segment 1107. No volatile chlorinated aromatic hydrocarbons, volatile unsaturated carbonyl compounds, nor volatile ethers were reported as discharged. Metals discharges ranging from 0.19 kg/yr for silver to over 13,000 kg/yr for zinc were reported, with most of these discharges located in the Houston Ship Channel/San Jacinto River area.

Besides the study cited above, a second study of permitted point source discharges funded by the Galveston Bay Foundation presented additional data generated under the 1988 SARA Title III Section 313 Toxics Release Inventory program. McCormick (1991) estimated the loading of "toxic chemicals" (a legal definition) to the Houston Ship Channel using: 1) the list of specific chemicals provided in the Toxics Release Inventory regulations; and 2) self-reported data from 97 industrial dischargers collected under the Toxics Release Inventory program.

Twenty-nine of these industries self-reported discharges of 68 of 320 toxic substances listed under the Toxics Release Inventory program. Segment 1007, extending from Greens Bayou to the Turning Basin (14 miles long), received an estimated 380,000 kg/year of listed toxic chemicals. McCormick noted this estimate included parameters such as ammonia, ammonium sulfate, and several inorganic acids which are required by state and federal discharge permits to be neutralized prior to discharge. When these easily-neutralized inorganic chemicals are not considered, the annual discharge of listed toxic chemicals to Houston Ship Channel Segments 1005, 1006, and 1007 was estimated as about 123,000 kg/year (McCormick, 1991).

Bypasses and Overflows

Raw or partially treated sewage can be discharged into Galveston Bay waters through bypasses or overflows from municipal wastewater collection systems. Wastewater collection systems were not designed to convey stormwater (intended to be conveyed in storm drains or via surface drainage in the streets). During rains, water enters the collection system thorough cracks in pipes (public and private) and through manholes leaks that have developed over the years from soil settlement, corrosion of concrete pipe, and in some cases, poor construction practices. Sufficient rainwater can enter the collection system to cause an overload, resulting in overflows of diluted sewage from manholes or overflow structures specifically installed to provide system relief.

Loading Estimates

Estimation of the loadings to Galveston Bay from bypasses and overflows is a difficult task. Bypasses and overflows are notoriously under-reported, in part because they are worst during bad weather. Any methods used require assumptions which are not necessarily easy to verify.

From a historical perspective, a 1986 study (Winslow and Associates, 1986) estimated the relative contribution of different wet weather pollutant sources to the Houston Ship Channel by collecting over 500 samples of storm data from numerous streams, land use areas, wastewater treatment plants, and parts of the wastewater collection system. This effort indicated that the total BOD loading from bypasses and overflows to the Houston Ship Channel was 3.1 million kg/year. By comparing all the loading sources, the authors concluded that bypasses and overflows contributed approximately 11 percent of the annual BOD load, seven percent of the TSS load, and seven percent of the ammonia load to the Ship Channel in 1986. These loading estimates are no longer likely to be accurate, due to actions currently being undertaken by the City of Houston (described below).

Preliminary results from a more recent survey by Guillen et al. (1994) documented the occurrence and magnitude of partially-treated effluent loadings from the immediate bay watershed. In 1991, a total of 789 reported bypass incidents accounted for 237.3 million gallons of partially treated sewage discharge; in 1992, 578 reported instances resulted in an estimated 451.0 million gallons of discharge. The majority (85 percent to 93 percent) of these bypasses occurred in the San Jacinto Watershed (excluding the area above the Lake Houston dam). Assuming these discharges have a composition similar to others which have been analyzed, an estimated 131,000 and 69,000 pounds of BOD were discharged during 1991 and 1992 respectively. In both cases the final amount that eventually reached the waterways and the final chemical composition was unknown. Many of the problems with collection systems were associated with infiltration during heavy storms and the general deterioration of older system components.

City of Houston Actions

Collection system overflows in the City of Houston currently occur in some locations as often as 20 times per year. This system consists of over 30 million feet of sewer in the public right-of-way, plus an approximately equal length of small-diameter pipe connecting private homes and businesses to the public sewer. The City of Houston is addressing this problem with an ambitious construction program to control wet weather overflows. The program consists of the construction of new relief sewers, treatment plant expansions, and the addition of wet weather facilities. In some locations, wet weather facilities will be designed to retain most stormwater flows in detention basins until after the storms have passed, and capacity once again exists in downstream sewers and treatment plants.

When the City of Houston system is constructed, untreated overflows will occur only during the largest rainfall events (greater than two to five year frequency storms). In addition to these facilities, the City of Houston has undertaken the largest sewer rehabilitation program in Texas (and possibly in the U.S.). This program will provide structural integrity to the sewer system and eliminate some of the stormwater flows currently entering the system. New design and construction practices will be utilized to minimize stormwater entry into the sanitary sewer system in the future.

Fecal Coliform Bacteria

All of the above point sources of waste water can contribute to the overall bacterial loading to Galveston Bay, however nonpoint sources are likely to be an even greater contributor. An analysis by Jensen (1992) focused on indicator fecal coliform bacteria inputs to Galveston Bay from permitted wastewater discharges, wastewater collection system leaks, overflows and excursions, partially treated wastewater from failed septic systems, and runoff from watershed areas.

Based on Jensen's analysis, treatment plants operating normally were not a significant source of fecal coliform bacteria. The study suggested that bypasses do not occur with sufficient regularity or magnitude to warrant quantification. Overflows and other collection system releases will continue to be a significant wet weather source of bacteria, but the data available suggest that it will be considerably less in the future than the estimates presented in Newell et al. (1992), which relied primarily on 1980s data. The contribution of fecal coliforms from malfunctioning septic systems is typically detectable only in the immediate locale, and then only during wet weather conditions (when other runoff sources will likely dominate anyway).

Unpermitted or Illegal Discharges

Fay et al. (1991) surveyed unpermitted discharges along nine shoreline segments of the Galveston Bay system and compared the magnitude of these unpermitted discharges to permitted discharges. The nine selected segments include Cedar Bayou (0901), Galveston Bay (2421), Double Bayou (unclassified segment), East Bay (2423), Chocolate Bayou (1107), Armand Bayou (1113), Dickinson Bayou (1103 and 1104) and Carancahua Lake and Bayou (unclassified segment). These nine segments were chosen to represent shorelines typical of the estuarine environment.

Fay et al. enumerated a total of 69 permitted discharges in the nine segments versus a total of 117 unpermitted discharges. The main permitted discharge types included oilfield related discharges, chemical and sewage plants, power plants and unknown/miscellaneous. Unpermitted discharge types, on the other hand, related to storm drains, dredge material, petroleum activity, lawn drainage, sewage discharge, and unknown/miscellaneous. A follow-up enforcement study by the Texas Natural Resource Conservation Commission indicated that most of the unpermitted discharges were not discharging illegally and were probably not a major source of pollution to the bay.

Produced Water

Produced water is an unwanted by-product of petroleum production (see box). On average, approximately nine barrels of water are recovered for each barrel of oil, although the "water cut" varies from well to well (one barrel = 42 gallons). The water-oil mixture from producing wells is separated by flotation or gravity separation in tank batteries, heat separation, skimming pits, or some combination of these methods, then is either re-injected underground or discharged to surface waters under a permit from the Texas Railroad Commission. The only discharges to surface waters permitted in Texas are coastal; inland produced brines are routinely disposed by injection due to potentially severe impacts to fresh receiving waters.

PRODUCED WATER IN GULF ESTUARIES

Oil field brines produced on the Texas coast range from slightly brackish to a salinity of five or six times seawater, with an ion composition skewed from both fresh and sea water. Brine typically contains soluble polynuclear aromatic hydrocarbons (PAHs) known to be toxic and carcinogenic, elevated metals, and radium-226 (in Texas, typically exhibiting less radioactivity than the minimum threshold for regulation as a Naturally Occurring Radioactive Material by the Texas Department of Health).

Typically, the coastal discharge of brine results in receiving water impacts that are more severe in enclosed areas with little circulation, and less severe in open water situations such as open bay waters or Gulf of Mexico. Typical impacts in estuaries include (Shipley, 1991; St. Pé, 1990; Roach et al., 1993*a*; 1993*b*; Caudle, 1993):

Hydrocarbons and salts contaminate sediments near discharges. Brines can be extremely dense, concentrating near the bottom and infiltrating the sediments. Sediment contamination is persistent for a period of years after discharges cease.

In sediments, toxicity severely depresses or eliminates benthic organisms to a substantial distance from discharges.

Fish populations and movements can be severely impacted, particularly in enclosed situations like bayous.

Hydrocarbons, including PAHs, are ingested and incorporated into the tissues of various aquatic organisms. Shorebirds feeding in the vicinity of brine discharges can accumulate significant body burdens of metals and hydrocarbons.

Marsh and other shoreline vegetation is killed or severely degraded by contact with brine.

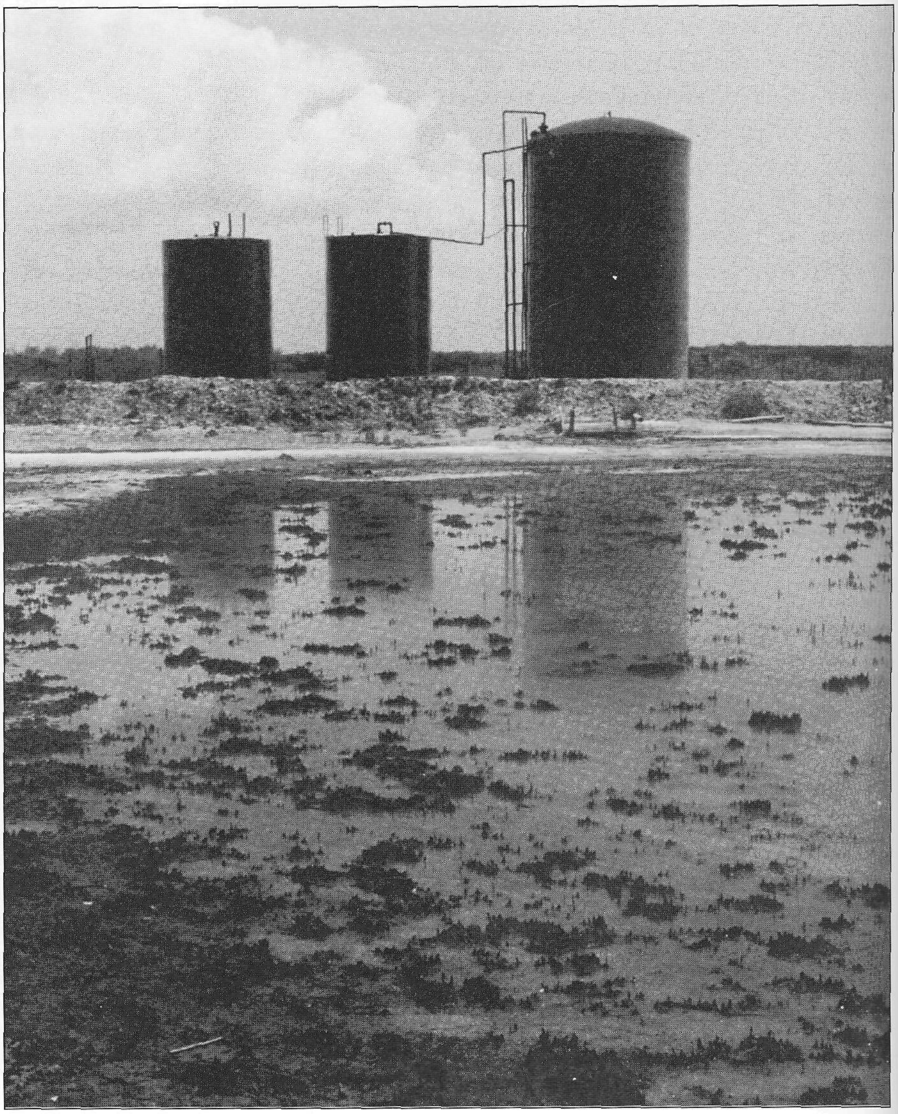
The Oil and Gas Division of the Texas Railroad Commission handles all permitting and enforcement for the discharge of produced water from oil and gas operations. Dischargers of produced brine in Texas are issued tidal disposal permits that allow up to 25 parts per million oil and grease, provided the discharge will not cause a violation of applicable Texas Surface Water Quality Standards, and which require permittees to report discharged volume and other information. Statewide Rule Eight, which includes a provision expressly forbidding pollution of offshore waters and adjacent estuarine zones, is the basis for actions concerning water pollution.

Texas Railroad Commission data indicates that some 93 discharges were permitted in 1991 to release up to 15.2 million gallons of produced brine per day to Galveston Bay and its tributaries. Of these, some 62 discharges were thought to be active, for an estimate of 5.8 million gallons per day actual discharge. Of this amount, however, approximately 3.4 million gallons per day were from one source, which voluntarily began deep-well injection in early 1993. Actual discharges into the bay vary greatly, depending upon the economic feasibility of oil production and the length of reservoir production (i.e., older fields yield proportionally more water).

Roach et al. (1993a; 1993b) evaluated some effects from produced water discharges to Galveston Bay. The study focused on impacts to sediments at Cow Bayou (a brackish urbanized bayou receiving a large volume of brine via ditch) and Tabbs Bay (an open-bay shoreline discharge location affected by wave action and tidal currents). Each location was sampled using a series of stations extending to several hundred meters from the discharge point, combined with reference stations for comparison, away from the discharges.

Data collected included: 1) number and kinds of benthic organisms; 2) analysis of sediments for petroleum hydrocarbons, metals, radium, and some other compounds; 3) toxicity tests on live laboratory organisms using both sediments (solid phase) and pore water extracted from sediments; 4) toxicity tests using sediment and water surface microlayer samples; 5) analysis of grass shrimp exposed to the samples for **stress proteins** (compounds that indicate sublethal environmental stress); and 6) analysis for PAH metabolites in bile of striped mullet collected at discharge locations (indicators of possible exposure to PAHs in the water column or via the food chain).

Findings reported by Roach, et al. (1993a; 1993b) included the following:



Source: R. Will Roach

Impacts resulting from produced brines from petroleum extraction include destruction of marsh vegetation due to excess salinity, shown here. Inland from the coast, produced waters are disposed by re-injection to the oil formation.

High concentrations of petroleum hydrocarbons, brine salts, and ammonia occurred in sediments near the discharges and generally decreased with distance from the discharge at both locations.

Benthic communities were non-existent or depressed near the discharge at both locations. The density of organisms, number of species, and community diversity (a mathematical index) all showed significant reductions extending to several hundred meters from the discharge.

Toxicity test results for two species of burrowing amphipods (sediments) and for sea urchin embryos/sperm (pore water) confirmed the toxicity of samples. Survival of both amphipods at the two stations nearest the Tabbs Bay discharge ranged from zero to about 20 percent, compared to some 90 percent for reference station samples.

Grass shrimp which survived exposure to re-suspended and whole sediments significantly accumulated two stress proteins for stations nearest the discharges.

Mullet from near both discharges had substantially higher concentrations of two PAH metabolites in bile than did comparison mullet from reference stations.

Although the Environmental Protection Agency does not currently regulate these discharges under its National Pollution Discharge Elimination System (NPDES), general NPDES permits for each of five discharge subcategories are currently being drafted. The subcategory of concern for the Galveston Bay system, the Coastal Subcategory, was issued on December 22, 1992 as a proposed rule, open for public comment. As currently drafted, this proposed rule would require "no discharge" to marshes, wetlands, swamps, bayous or coastal bays from all wells, including stripper wells.

HUMAN IMPACTS: NONPOINT SOURCES AND LOADINGS

Overview of Nonpoint Sources

We now know that the influx of conventional pollutants from point sources of wastewater peaked in the 1960s and has declined since. This is due in large part to the creation of the first federal Water Quality Act, and the subsequent permitting, compliance, and enforcement activities which began nearly three decades ago.

In contrast, all indications are that nonpoint sources of pollutants have steadily increased to the present day, and significantly influence the water and sediment quality in various portions of Galveston Bay. Effects of these pollutants are seen in low dissolved oxygen in urban bayous and other poorly flushed tributaries, possible toxic contamination from metals or trace organic compounds, and closure of about half of the bay to oyster harvest, due to elevated bacteria levels. The upper Houston Ship Channel remains a significant region of concern, due in large part to runoff from the greater Houston area. Nonpoint sources, because of their diffuse nature and association with runoff over extensive land areas, present a major management challenge (see box).

Source: Galveston Bay National Estuary Program

One of the bay's nonpoint sources of pollution. From stormwater runoff each year, the bay receives oil equivalent to a 130,000 barrel spill—an amount equating to 40 percent of the historic Exxon Valdez *spill. Much of this oil originates from parking lots and city streets, including what has been dumped down storm sewers since the last rainfall.*

For Galveston Bay, urban land uses in the lower watershed pose the greatest challenge in the NPS arena. In general, the net effect of urbanization is to increase pollutant export by at least an order of magnitude over pre-development levels (Schueler, 1987). A variety of urban sources have been generally identified as NPS contributors: bird and pet populations, street litter accumulation, tire wear of vehicles, oil from car crankcases, fertilizer and pesticide application, eroded areas, abrasion of road surfaces by traffic, and construction activities. Water quality constituents of concern

SOME GENERAL CHARACTERISTICS OF NONPOINT SOURCE POLLUTION

Nonpoint source pollution (NPS) has become the largest single factor in preventing attainment of water quality standards nationwide. Novotny and Chesters (1981) described some general characteristics of nonpoint source pollution:

> Nonpoint source discharges enter surface waters in a diffuse manner and at intermittent intervals that are related mostly to the occurrence of rainfall.
>
> Pollution arises over an extensive area of land and is in transit overland before it reaches surface waters.
>
> Nonpoint sources generally cannot be monitored at their point of origin, and their exact source is difficult or impossible to trace.
>
> Elimination or control of pollutants must be directed at specific sites.
>
> In general, the most effective and economical controls are land management techniques and conservation practices in rural zones and architectural control in urban zones.
>
> Compliance monitoring for nonpoint sources is carried out on land rather than in water.
>
> Nonpoint source pollutants cannot be measured in terms of effluent limitations.
>
> The extent of nonpoint source pollution is related, at least in part, to certain uncontrollable climatic events, as well as geographic and geologic conditions, and may differ greatly from place to place and year to year.
>
> Nonpoint sources are derived from operations on extensive units of land, as opposed to industrial activities that typically use repetitive operations on intensive (small) units of land.

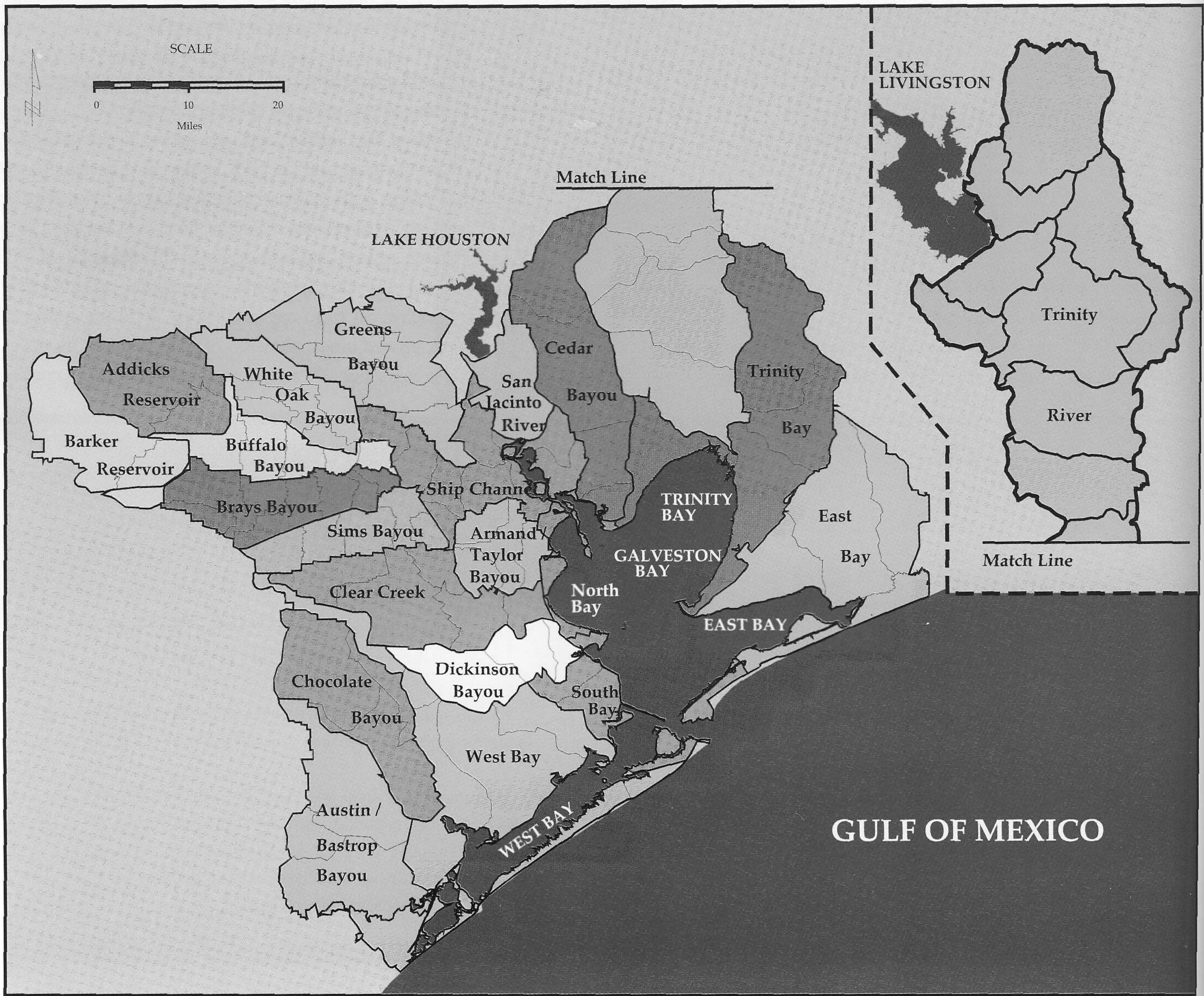
in urban runoff include sediments, nutrients, oxygen-demanding compounds, oil and grease, bacteria, heavy metals, and synthetic organic chemicals.

Nonpoint pollutant loading is closely tied to land use. Of all the urban land uses, low-density residential zones and open areas yield the lowest NPS loads, while highest pollution loads are associated with high-density commercial areas, industrial centers and, above all, construction sites. During construction activities considerable areas are stripped of vegetative cover, exposing open soil. The NPS loadings from construction areas can be an order of magnitude higher than other land uses, and can dominate the total NPS loadings in some watersheds.

In general, rural nonpoint sources are related to agricultural and silvicultural activities, such as fertilizer and pesticide application, tillage and logging. Since these operations do not occur continuously, nonpoint source loads from rural areas can fluctuate significantly from storm to storm. For many agricultural areas, high sediment and nutrient loads are observed in the spring, when plowing and agricultural chemicals are added to the soil. Much lower loads are observed after harvesting, when cultivated fields lie fallow or are grazed by livestock. Because major reservoirs on both the Trinity and San Jacinto are downstream of most agricultural activities in the watershed, these activities have limited influence on Galveston Bay.

Pollutant Loadings from Runoff

Until recently, no comprehensive estimates of nonpoint pollutant loadings to the Galveston Bay system were available. Recently, Newell et al. (1992) have provided such a study. NPS loads for a total of eight different water quality constituents in



Source: Newell et al., 1992

FIGURE 6.18. *Boundaries for watersheds (bold lines) and subwatersheds (fine lines) of the lower Galveston Bay watershed. These land units contribute variable types and amounts of pollutants to Galveston Bay during runoff. Land use generally determines the kind and severity of pollution, with the urban subwatersheds of greater Houston posing the greatest concern.*

TABLE 6.3. Nonpoint Source Loads to Galveston Bay by Land Use for a Year With Average Rainfall.

	Land Use Type								
Constituent	High Density Urban	Residential	Open	Agricultural	Barren	Wetlands	Water	Forest	Total
Runoff Volume									
1,000 ac-ft	766	371	567	593	21	187	164	345	3,014
(% of Total)	(25)	(12)	(19)	(20)	(1)	(6)	(5)	(11)	(100)
TSS									
Million kg	157	46	49	147	57	9	0	17	481
(% of Total)	(33)	(10)	(10)	(31)	(12)	(2)	(0)	(3)	(100)
Total Nitrogen									
1,000 kg	1,985	1,561	1,056	1,142	134	192	0	353	6,422
(% of Total)	(31)	(24)	(16)	(18)	(2)	(3)	(0)	(5)	(100)
Total Phosphorus									
1,000 kg	350	362	84	264	15	14	0	26	1,113
(% of Total)	(31)	(32)	(8)	(24)	(1)	(1)	(0)	(2)	(100)
BOD									
Million kg	8	7	4	3	0	1	0	3	26
(% of Total)	(31)	(26)	(16)	(11)	(1)	(5)	(0)	(10)	(100)
Oil and Grease									
Million kg	12	2	0	0	0	0	0	0	14
(% of Total)	(87)	(13)	(0)	(0)	(0)	(0)	(0)	(0)	(100)
Fecal Coliform									
$x10^{15}$ col	208	101	17	18	0	4	0	7	355
(% of Total)	(59)	(28)	(5)	(5)	(0)	(1)	(0)	(2)	(100)
Dissolved Cu									
kg	2,930	1,419	2,167	2,269	80	716	0	1,318	10,900
(% of Total)	(27)	(13)	(20)	(21)	(1)	(7)	(0)	(12)	(100)
Pesticides									
kg	378	183	70	73	3	0	0	43	749
(% of Total)	(50)	(24)	(9)	(10)	(0)	(0)	(0)	(6)	(100)

Source: Newell et al., 1992

runoff were calculated: sediment, nutrients (total phosphorous and total nitrogen), biochemical oxygen demand, oil and grease, fecal coliform bacteria, heavy metals, and synthetic organic constituents. Typical pollutant concentrations were estimated from available NPS data, in particular, data collected from previous Houston-area NPS studies. Total NPS loads were then calculated by multiplying runoff volumes estimated by a Soil Conservation Service hydrologic model (U.S. Soil Conservation Service, 1986) with the appropriate NPS concentration for each land use.

This study took a geographic approach to identify regions contributing the greatest NPS loadings to the bay system. For the study, the Galveston Bay watershed was divided into 21 watersheds and 100 subwatersheds (FIGURE 6.18). Three rainfall scenarios were formulated from rain gauge data in the basin: an average year, a wet year with a ten-year probability, and an individual storm. The rainfall amounts were transformed into runoff volume using the U.S. Soil Conservation Service curve number method.

Within the study area, land use was mapped using LANDSAT satellite image interpretation. (LANDSAT is an unmanned satellite system which acquires images of the earth's surface features.) A more detailed summary of land use in the local watershed is provided in Chapter Five, including a land use map (see FIGURE 5.2). The technology utilized produced a 30 m by 30 m resolution, allowing geographic information system calculation of subwatershed loadings for each constituent.

Geographic and Land Use Targeting of Nonpoint Sources

Within the study area, type of land use was the main factor determining loadings. For example, "high density urban" land uses across the watershed contributed approximately 87 percent of the annual oil and grease loading, 59 percent of the annual fecal coliform bacteria loading (estimate does not include overflow, the study was strictly a wash-off analysis), 31 percent of total nitrogen and total phosphorus loading, and 50 percent of the annual pesticide loadings from the study. Urban areas were also shown to be

TABLE 6.4. Nonpoint Source Loads to Galveston Bay for an Average Year by Watershed.

Watershed	Area (sq mi)	Runoff Volume (1,000 ac-ft)	Total Susp. Solids (Million kg)	Total Nitrogen (1,000 kg)	Total Phos-phorus (1,000 kg)	Bio-chemical Oxygen Demand (Million kg)	Oil and Grease (Million kg)	Fecal Coli-form ($x10^{15}$ Col)	Diss. Copper (kg)	Pesti-cides (kg)
Addicks Reservoir	134	82	22	195	36	0.7	0.4	9	312	20
Armand/ Taylor Bayou	77	70	12	167	29	0.7	0.5	11	255	22
Austin/ Bastrop Bayou	213	121	21	245	44	0.9	0.2	9	442	21
Barker Reservoir	122	71	32	181	31	0.6	0.2	6	271	14
Brays Bayou	127	147	29	406	75	1.7	1.7	34	561	63
Buffalo Bayou	105	116	22	337	65	1.4	1.3	27	445	51
Cedar Bayou	211	153	26	321	58	1.2	0.3	13	576	30
Chocolate Bayou	170	95	19	188	36	0.6	0.1	5	354	15
Clear Creek	182	138	22	301	51	1.2	0.7	16	503	34
Dickinson Bayou	101	60	8	130	21	0.5	0.2	6	223	13
East Bay	288	193	26	388	68	1.6	0.5	17	679	36
Greens Bayou	209	184	30	497	92	2.1	1.4	34	702	66
North Bay	25	25	4	65	11	0.3	0.2	5	94	9
San Jacinto River	68	65	8	126	22	0.5	0.2	7	202	14
Houston Ship Channel	166	198	34	498	90	2.0	1.9	39	713	74
Sims Bayou	93	91	16	235	41	1.0	0.8	17	346	33
South Bay	78	68	10	138	24	0.6	0.6	12	211	22
Trinity Bay	317	225	26	356	59	1.5	0.3	12	708	32
Trinity River	1,099	572	62	877	124	4.3	0.5	27	2,110	82
West Bay	344	212	30	405	68	1.6	0.9	21	706	44
White Oak Bayou	110	128	24	365	69	1.5	1.3	29	488	54
Total Project Area	**4,238**	**3,010**	**481**	**6,420**	**1,110**	**26.3**	**14.2**	**355**	**10,900**	**749**
Median	134	121	22	301	51	1.2	0.5	13	445	32
Maximum	1,099	572	62	877	124	4.3	1.9	39	2,110	82
Minimum	25	25	4	65	11	0.3	0.1	5	94	9

Source: Newell et al., 1992

intense source zones for pesticides. Loading estimates by land use type for a year with average rainfall are given in TABLE 6.3.

The geographic distribution of loadings was determined based on land use and runoff data. The load maps produced for this project (FIGURES 6.19–6.23) identified subwatersheds with high nonpoint source load generation. As expected from land use findings, the highly urbanized areas in Houston, Baytown, Texas City, and Galveston contributed the highest loads per unit area for all water quality constituents. Of these constituents, fecal coliform bacteria and oil and grease loads were almost entirely associated with the urban areas. Loading estimates for the individual subwatersheds for a year with average rainfall are given in TABLE 6.4.

Discussion

The amount of NPS pollution was found to be very sensitive to the amount of runoff. The runoff and loads for a wet year were 40-60 percent higher than those found for the average year. Significantly, a large individual storm event (equal to storm size that occurs on the average once per year) was found to contribute approximately 15 to 20 percent of the total annual nonpoint source load to the bay. These data indicated that a significant portion of the annual loads occur during a few of the largest rainfall events during the year.

The geographic approach used in the study of Newell et al. indicated that the highest erosion rates, and thus greatest sources of sediment were occurring in a wedge-shaped area, having a point at the mouth of the Ship Channel and reaching westward through Houston to the watersheds upstream of Barker/Addicks reservoirs. The high sediment loads were attributed to a combination of erosion in urban land use areas in the Houston vicinity and of barren land in the rural western watersheds.

Compared to the pollutant loads generated by urban areas, agricultural loadings were smaller. Much of the lower watershed involved in agriculture is devoted to rice production, which may result in significantly lower pollutant loads of sediment, nutrients, and pesticides when compared to row crops (McCauley, 1991).

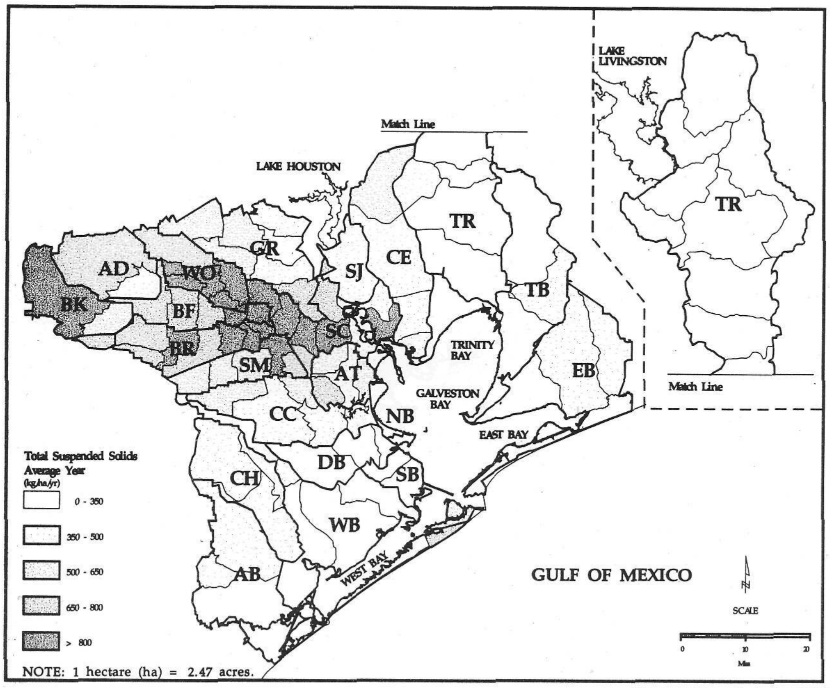
While high pollutant concentrations could occur seasonally (for example, nutrients just after fertilizer application), low concentrations have been observed during much of the growing season (Brown et al., 1978). During the growing season water in rice fields is impounded behind small dikes, limiting potential for erosion and pollutant release. The complicated hydrology of rice fields and the variable water quality over time make it very difficult to estimate an average NPS-related concentration in rice-field runoff.

Note that the forgoing information addresses the source of NPS pollutants. What happens to these pollutants once they reach a bayou, river, or the bay is a separate and difficult issue. Actual impacts of local NPS pollutants on the bay are difficult to assess without analyzing the change in pollutant concentrations in Galveston Bay itself. For example, NPS loads enter the bay intermittently as relatively brief slugs of pollutants in large volumes of runoff, from numerous entry points. The amount, timing, and duration of these NPS events are determined by rainfall conditions. Discharge from Lake Livingston and Lake Houston complicates this assessment, as the reservoirs change the timing and water quality of the discharge from the Trinity and San Jacinto rivers to the bay.

Septic Tanks

Septic tanks near Galveston Bay have the potential to contribute nutrients and human pathogens to waters of the estuary (see Chapter Nine). The soils in the immediate watershed virtually assure numerous septic tank failures, since the fine-grained clays have an extremely slow percolation rate. Overall, however, septic tanks do not likely contribute a substantial portion of the total fecal coliform bacteria loading to Galveston Bay (Jensen, 1992). Leaks from failing septic systems do affect local areas, particularly tributaries such as Dickinson Bayou, where limited dilution occurs. Also, numerous (perhaps most) septic tank failures go unreported, inhibiting estimates of their impact on the bay.

Malfunctioning septic tanks were included in a study reported by Guillen et al. (1994). During 1992 a total of 166 septic tank violations were reported to designated municipal agents and/or the Texas Natural Resource Conservation Commission. Using common industry estimates of the average flow from a malfunctioning septic system Guillen et al. estimated that a total of 4,445,030 gallons of partially treated effluent from faulty septic systems had

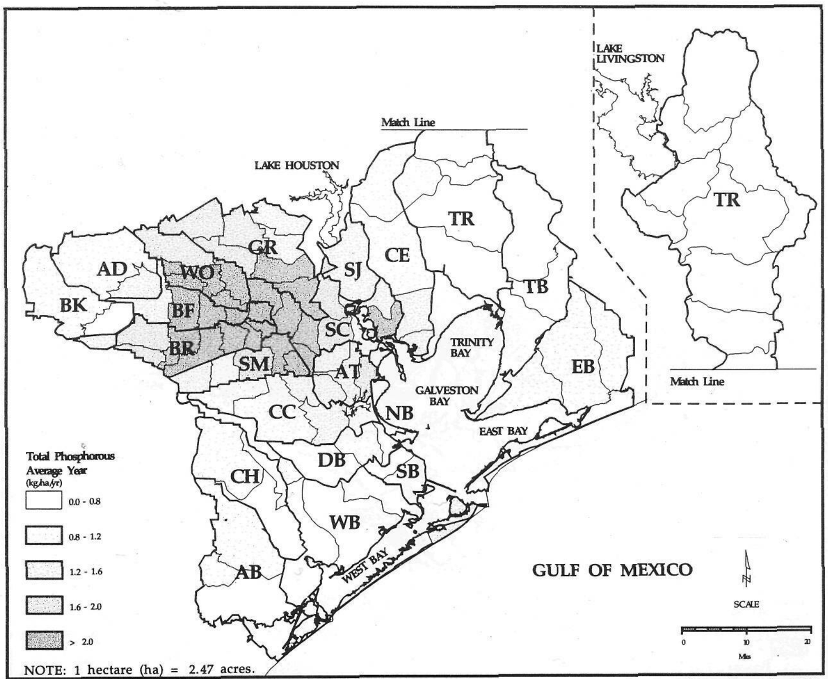


Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou
BR Brays Bayou			

FIGURE 6.19. *Total suspended solids in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. A major constituent is sediment, particularly from construction sites and barren or eroding lands.*

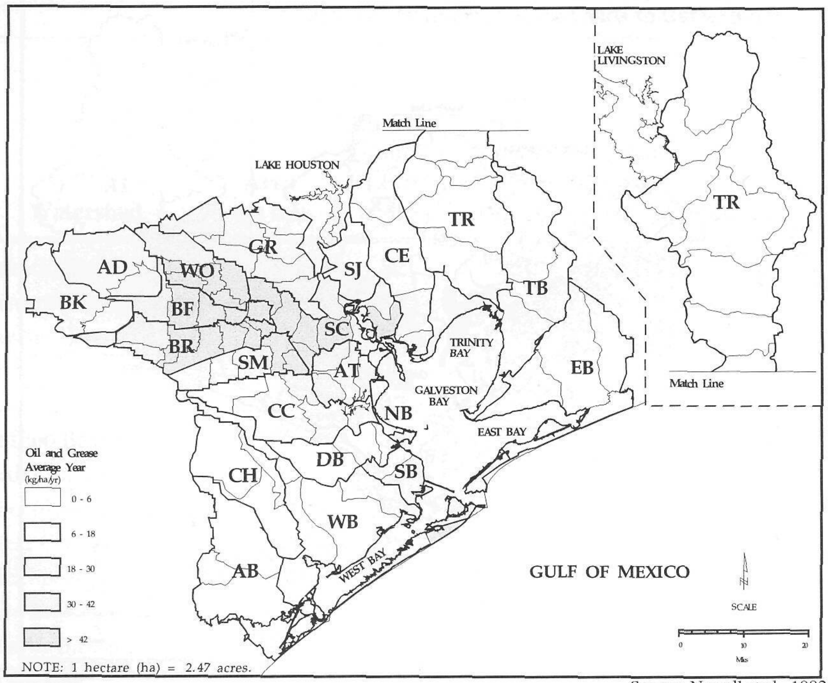


Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou
BR Brays Bayou			

FIGURE 6.20. *Total phosphorus in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. Phosphorus, a nutrient which can overstimulate algae growth, tends to attach to sediment particles.*

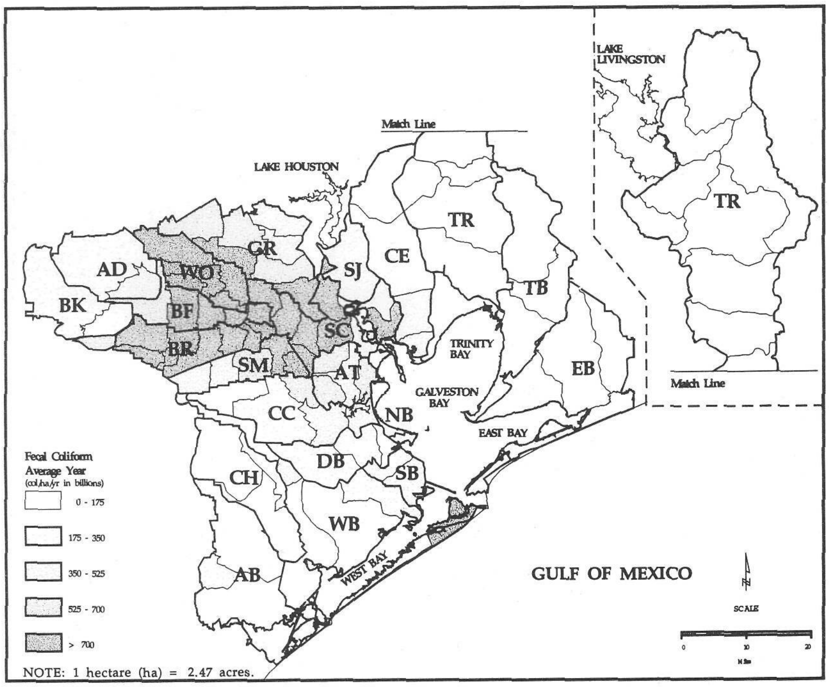


LEGEND

Source: Newell et al., 1992

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou

FIGURE 6.21. *Oil and grease in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. Loading from this source totals some 40 percent of the historic* Exxon Valdez *spill annually. Oil and grease contain numerous specific compounds, many of which are toxic. Sources include engine drippings and purposeful dumping of motor oil.*



LEGEND

Source: Newell et al., 1992

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou

FIGURE 6.22. *Fecal coliform bacteria in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. These bacteria indicate contamination from warm-blooded animal or humans sources, including pets, wildlife and sewage. Not included are sewage sources from septic tanks and municipal sewage system bypasses and overflows.*

discharged into the Galveston Bay watershed during 1992. The exact chemical composition and final amount that eventually reached waterways via overland flow or storm sewers was unknown. The majority (83 percent) of complaints occurred in the San Jacinto Watershed (excluding the area above the Lake Houston dam). The majority of problems were associated with poor system design and/or insufficient soil drainage.

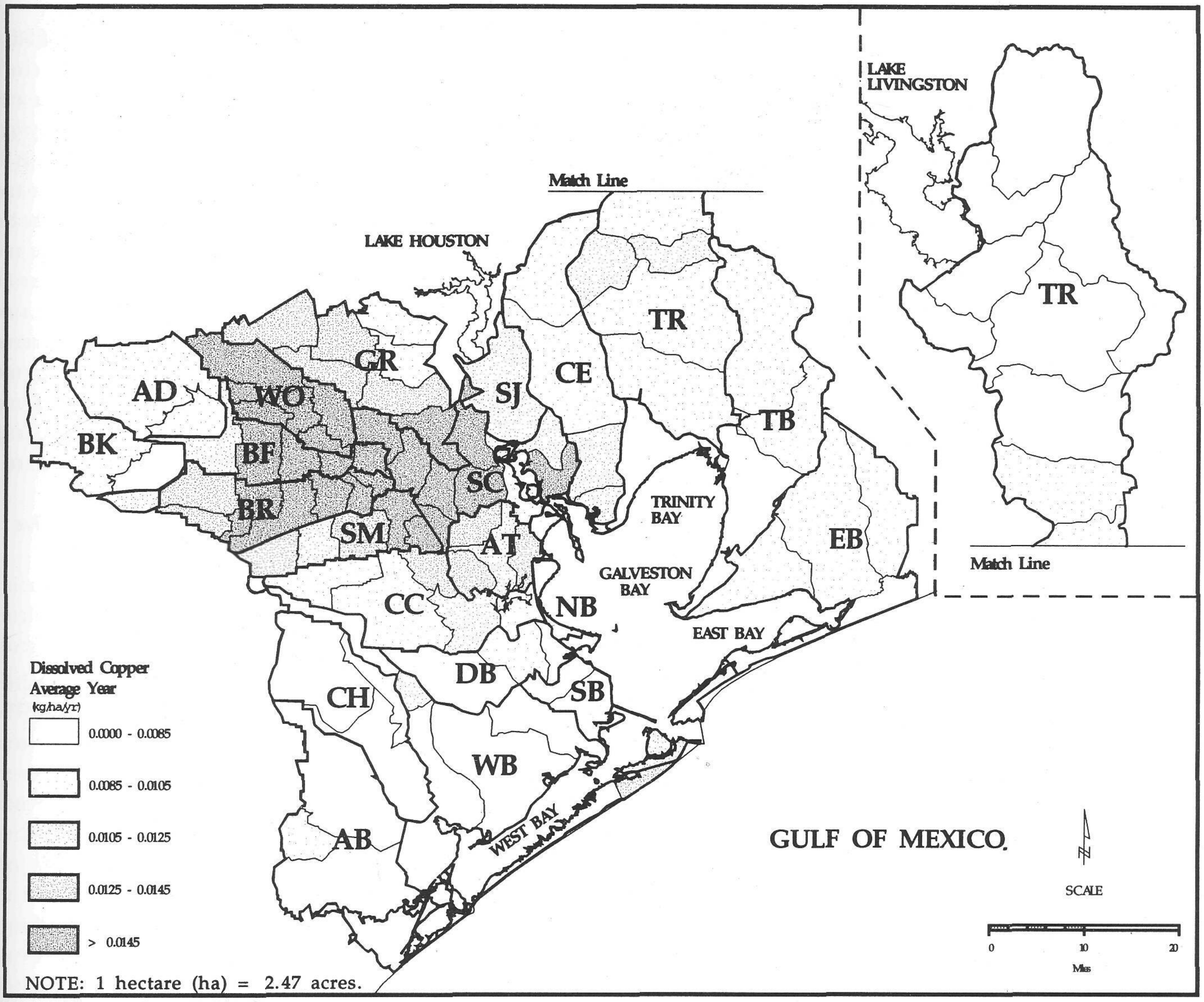
Marina/Boater Impacts

Evidence exists from studies in other parts of the country that marinas and their associated boats can be sources of pollutants, including heavy metals, fecal coliform bacteria, and nutrients (North Carolina Department of Environment, Health, and Natural Resources, 1991). Improperly designed marinas with poor circulation can also reduce flushing and, during times of minimal water movements, concentrate pollutants, deplete oxygen, and cause serious environmental harm, including fish kills.

Galveston Bay, particularly in the Clear Lake area, contains a very high concentration of recreational vessels (see Chapter Four). Until recently, there were few locations to pump out boat sewage and, consequently, much of the boat sewage was discharged directly into Galveston Bay and/or Clear Lake. However, recently a private entrepreneur has built both portable and stationary sites in Clear Lake (Maritime Sanitation, 1992).

Four recreational marinas and one boat canal subdivision were studied by Guillen et al. (1993) during May and July, 1992. These included the Galveston Yacht Club, Lafayette Landing, Houston Yacht Club, South Shore Harbor, and Jamaica Beach. Surface water and recently-deposited sediment samples were collected from four locations at each marina site. These locations included an inside station (furthest away from outlets to adjacent water bodies), an entrance station at the opening of the marina, a near-field station (within 0.25 mi from the entrance), and a far-field site (usually ≥ 0.5 mi from the entrance). General conclusions were:

> Fecal coliform bacteria concentrations generally increased as one progressed from open waters inward in each marina system. State water



Source: Newell et al., 1992

LEGEND

AB	Austin/Bastrop Bayou
AD	Addicks Reservoir
AT	Armand/Taylor Bayou
BF	Buffalo Bayou
BK	Barker Reservoir
BR	Brays Bayou
CC	Clear Creek
CE	Cedar Bayou
CH	Chocolate Bayou
DB	Dickinson Bayou
EB	East Bay
GR	Greens Bayou
NB	North Bay
SB	South Bay
SC	Ship Channel
SJ	San Jacinto River
SM	Sims Bayou
TB	Trinity Bay
TR	Trinity River
WB	West Bay
WO	White Oak Bayou

FIGURE 6.23. Dissolved copper in storm water runoff from Galveston Bay sub watersheds in a year with typical rainfall.

quality standards for fecal coliforms were exceeded at the inner stations and state shellfish standards (14 colonies per 100 mL) were violated at the Houston Yacht Club. The outer stations of the Clear Lake marinas may also have been influenced by human activities unrelated to boats, for example urban runoff and septic system failures.

Dissolved oxygen generally decreased as one progressed from open waters inward in each marina system. Lowest levels were recorded at the South Shore Harbor inner station. Dissolved oxygen at the inner stations of Jamaica Beach and South Shore Harbor violated the state water quality standard of 4.0 mg/L.

Copper and lead showed apparently increasing contamination toward the inner stations of each marina. This suggested that long term accumulation of copper and lead in sediments may be occurring.

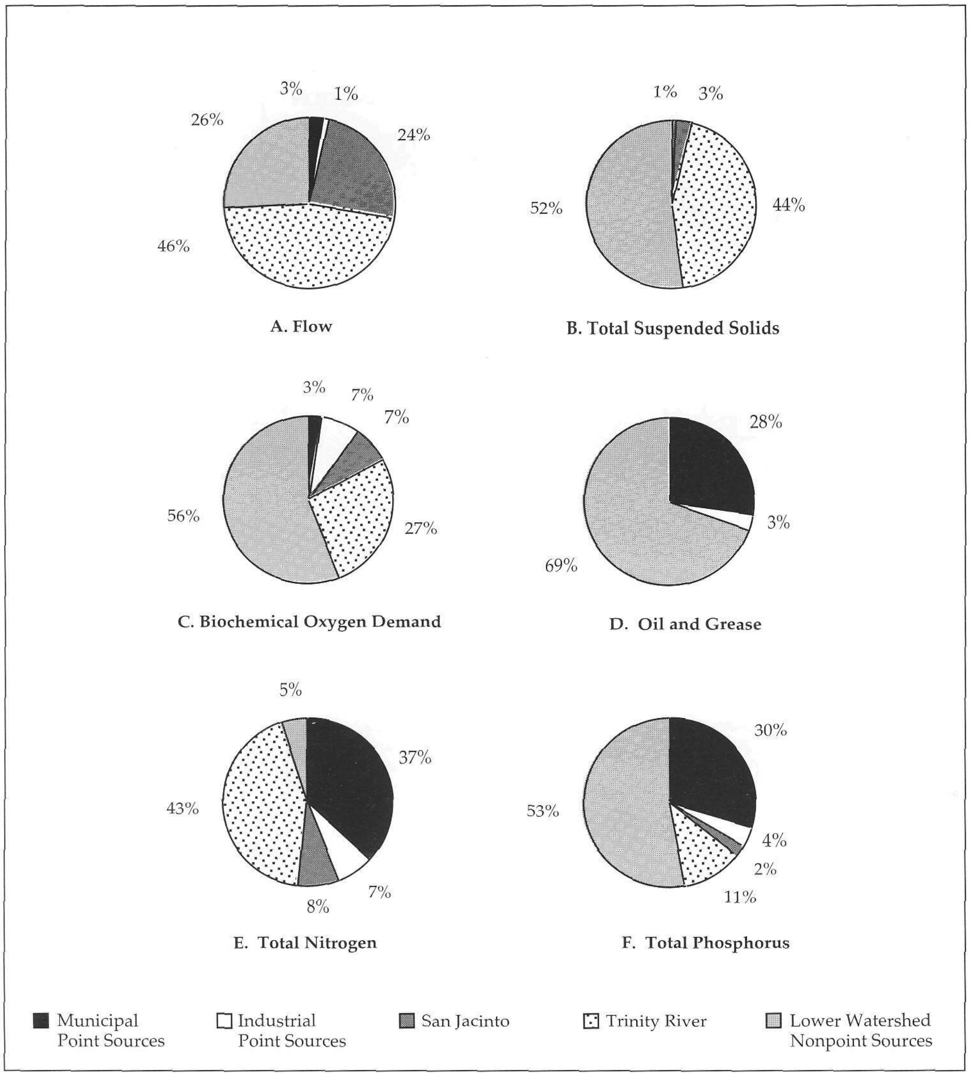


FIGURE 6.24. Bay-wide analysis: the relative contribution of selected constituents to the Galveston Bay system from five major sources. These estimates represent a synthesis of various recent studies described in this chapter.

POLLUTANT LOADING TO GALVESTON BAY: A SYNTHESIS

Galveston Bay is affected by diverse major influences on the quality of its water and sediments. The complex physical, chemical, and biological processes in the bay make these influences difficult to tease apart. However, the managers of the bay, who seek to identify and alter the most negative influences, have great interest in determining the relative roles of the major sources of pollution. Managers are interested in both the entire system and in portions of the system such as the upper Houston Ship Channel, which have traditionally received the greatest wastewater volume.

Relative Contributions From Five Sources

In this section, relative loadings from five of the bay's major pollution sources were compared for each of several key water quality constituents. The sources considered for this analysis were:

Municipal Point Sources. Approximately 559 permitted wastewater treatment plants provide a total flow of approximately 135 trillion gallons per year. Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Goodman, 1989).

Dissolved arsenic levels were generally low and did not exceed state criteria for chronic (long-term) exposure. There was nonetheless an apparent increasing trend of arsenic contamination toward the inner stations of each marina. This suggests that long-term accumulation of arsenic in sediments may be occurring.

Guillen et al. (1993) concluded that most water quality impacts associated with marinas are localized. Dissolved oxygen levels were generally depressed, severely at the Jamaica Beach finger canals and at South Shore Harbor. Oxygen problems were least severe at the more openly designed Galveston Yacht Club and at the Houston Yacht Club, which employ bulkheads that do not extend to the bottom. The Houston Yacht Club design allows water to enter the marina from below the bulkhead and also at the marina entrance. The other facilities' primary flushing corridor is limited to main entrances only.

Industrial Point Sources. Some 247 facilities in the immediate watershed provide about 39 billion gallons of "process water" per year (not including cooling water). Loadings were derived from Armstrong and Ward (1994), excepting pesticides (Goodman, 1989).

The San Jacinto River. This second-largest river feeding the bay delivers flow from 2,828 sq mi of watershed draining into Lake Houston. (Note that some of the loadings from the San Jacinto watershed originate from upstream point sources). Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Newell et al., 1992).

The Trinity River. Some 26,000 sq mi of watershed (including Dallas and Fort Worth) are drained by the Trinity. Net loadings were measured at Romayor, Texas, located several miles downstream of the Lake

Livingston dam. (As with the San Jacinto River, loadings represent a mixture of nonpoint and point sources). Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Newell et al., 1992).

Local nonpoint sources from the lower watershed. Runoff from the 4,600 sq mi watershed immediately surrounding the bay reaches the estuary from a variety of bayous, small streams, stormwater outfalls, and overland drainage. Loadings were derived from Newell et al. (1992), excepting PCBs (Armstrong and Ward, 1994) and PAHs (national means reported by Cole et al., 1984).

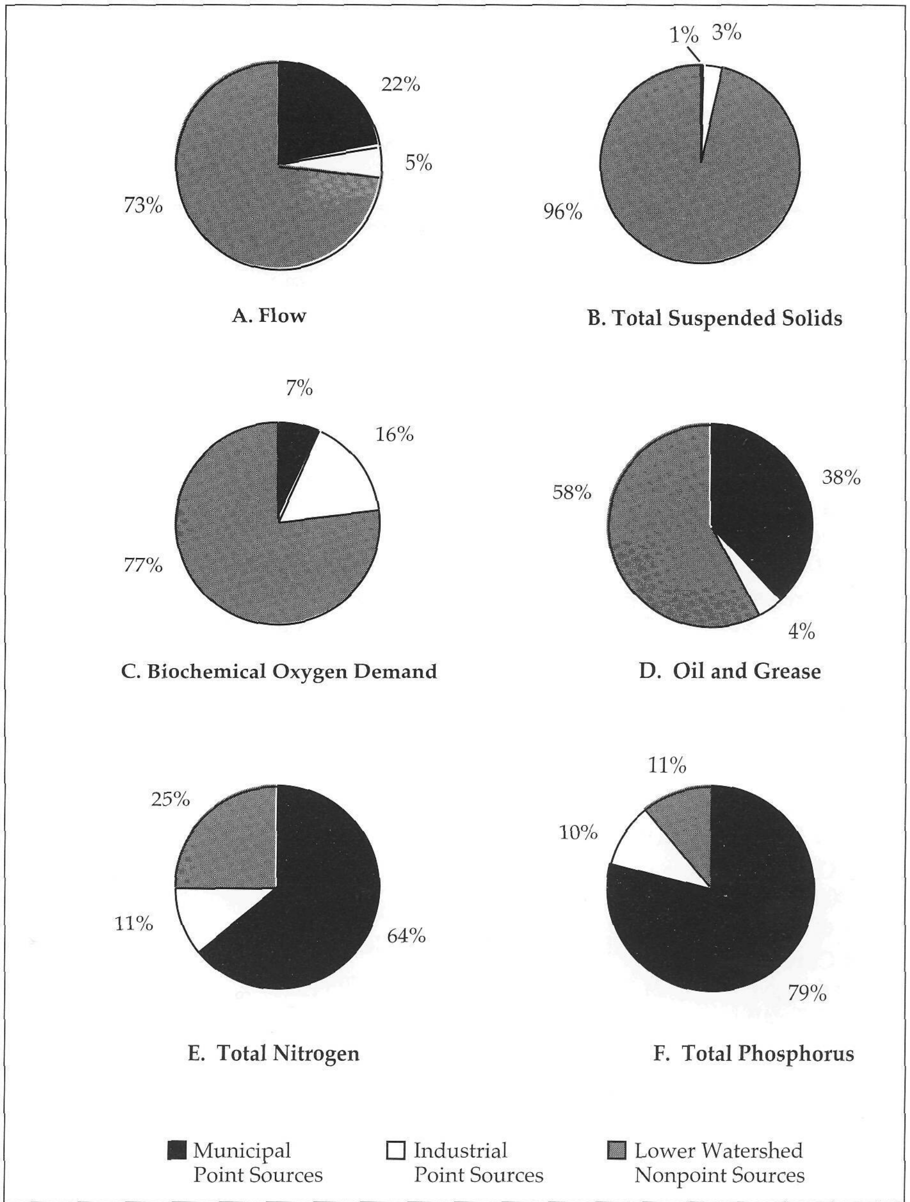


FIGURE 6.25. Upper Houston Ship Channel analysis: the relative contribution of selected constituents to the upper Houston Ship Channel (upstream from the mouth of the San Jacinto River) from five major sources. These estimates represent a synthesis of various recent studies described in this chapter.

Reflecting the interests of bay managers, loading estimates for the five pollutant sources were calculated for two different geographic areas: 1) for the entire bay system; and 2) for the upper Houston Ship Channel only, upstream from the mouth of the San Jacinto River. Geographically, all sources within the watershed were used for the baywide analysis, while the Houston Ship Channel analysis utilized an appropriate set of subwatersheds based on known hydrology. These were: Buffalo Bayou (including Addicks and Barker reservoirs), Brays Bayou, Greens Bayou, Sims Bayou, White Oak Bayou, and the local Houston Ship Channel drainage (see Newell et al., 1992). Data from the Texas Natural Resource Conservation Commission water quality segments 1005, 1006, 1007, 1013, 1014 were used to estimate point source loads to the channel.

Other potential sources of pollutants not considered in this comparison include groundwater, constituents in rainfall itself, boats, mobile animal sources, and oil and chemical spills (some of these are considered in the next section). Internal bay sources, such as the cycling of contaminants from the sediments to the water and net transport from the Gulf to the bay were also not evaluated. The comparison was intended to show the relative contribution of the most important inputs to the Galveston Bay system.

Loadings to the Entire Galveston Bay System

Loadings to the bay system are given in TABLE 6.5, with relative contributions from the five sources shown in the form of pie charts for selected constituents (FIGURE 6.24). As described in Chapter Four, the Trinity River is the largest source of flow to Galveston Bay. Over an entire year, point sources contribute less than five percent of the total flow into the bay.

Local nonpoint sources are the largest source of total suspended solids to the bay, contributing slightly over 50 percent of the 914 million kg/yr of sediment. The Trinity River, even with the effects of the Lake Livingston reservoir, was a close second. Point sources contributed less than one percent of the total suspended solids loading to the bay. The location of sediment delivery is important–for example sediment loading to the Trinity delta is highly desirable to maintain wetlands.

Local nonpoint sources also generated over half of the bay's annual BOD loading, with point sources providing less than ten percent of the total loading. Municipal point sources were the source of about one-third of the nitrogen and phosphorus load to

TABLE 6.5. Bay-Wide Analysis: Relative Contributions of Pollutants From Five Major Sources.

Point Source Constituent	Municipal Point Sources	Industrial Point Sources	San Jacinto River	Trinity River	Lower Watershed Nonpoint Sources	Total
Flow						
Million ac-ft/yr	0.4	0.1	2.8	5.5	3.0	11.8[1]
(% of Total)	(3)	(1)	(24)	(46)	(25)	(100)
Total Susp. Solids						
Million Kg/yr	2.7	7.0	25.4	398.4	481.0	914.5
(% of Total)	(0)	(0)	(3)	(44)	(53)	(100)
BOD						
Million Kg/yr	1.4	3.3	3.5	13.0	26.3	47.5
(% of Total)	(3)	(7)	(7)	(27)	(55)	(100)
Oil and Grease						
Million Kg/yr	5.7	0.6	0.0	0.0	14.2	20.5
(% of Total)	(28)	(3)	(0)	(0)	(69)	(100)
Total Nitrogen						
Million Kg/yr	7.1	1.3	1.5	8.2	1.1	19.2
(% of Total)	(37)	(7)	(8)	(43)	(6)	(100)
Total Phosphorus						
Million Kg/yr	3.6	0.4	0.2	1.3	6.4	11.9
(% of Total)	(30)	(4)	(2)	(11)	(54)	(100)
Total Arsenic						
1,000 Kg/yr	16.3	3.8	3.9	50.7	29.0	103.7
(% of Total)	(16)	(4)	(4)	(49)	(28)	(100)
Total Cadmium						
1,000 Kg/yr	5.6	0.8	2.7	14.2	5.5	28.8
(% of Total)	(20)	(3)	(9)	(49)	(19)	(100)
Total Chromium						
1,000 Kg/yr	21.9	10.2	46.7	119.7	10.0	208.5
(% of Total)	(11)	(5)	(22)	(57)	(5)	(100)
Total Copper						
1,000 Kg/yr	18.8	9.1	65.4	129.1	49.5	271.9
(% of Total)	(7)	(3)	(24)	(47)	(18)	(100)
Total Lead						
1,000 Kg/yr	23.0	2.4	43.9	365.2	138.4	572.9
(% of Total)	(4)	(0)	(8)	(64)	(24)	(100)
Total Mercury						
1,000 Kg/yr	0.2	0.0	0.8	2.8	0.9	4.6
(% of Total)	(3)	(1)	(17)	(60)	(19)	(100)
Total Zinc						
1,000 Kg/yr	83.9	30.0	232.1	639.0	396.9	1381.9
(% of Total)	(6)	(2)	(17)	(46)	(29)	(100)
PCBs						
Kg/yr	0.0	15.7	0.0	38.0	61.3	115.0
(% of Total)	(0)	(14)	(0)	(33)	(53)	(100)
Pesticides						
Kg/yr	588.0[2]		170	575	749	2082
(% of Total)						(100)
PAHs						
Kg/yr	-	0.0	-	-	371.0	>371
(% of Total)						(100)

[1]Note this value is about 15 percent higher than given in Chapter Five; point sources were include here and different sources of data were consulted

[2]This represents the combined municipal and industrial point source loading

the bay. The Trinity River contributed 43 percent of the total nitrogen load, while the local nonpoint sources yielded 54 percent of the total phosphorus load.

The Trinity River was the largest source of all seven of the metals analyzed, ranging from a 46 percent to 64 percent contribution. Industrial sources were minor contributors bay-wide (less than five percent in all cases) while municipal dischargers were responsible for between ten and 20 percent of the total arsenic, cadmium, and chromium loading. Local nonpoint sources were also significant contributors and provided between 18 percent and 29 percent of the metals loading for total arsenic, total cadmium, total copper, total lead, total mercury, and total zinc. Note that these data were based on analytical methods for metals whose overall accuracy has been questioned (described previously in this chapter).

For PCBs, the analysis performed by Armstrong and Ward (1994) indicated that the local tributary loadings (consisting mostly of local nonpoint sources with some point sources) contribute 61 kg/yr of PCBs to the bay, the largest source. Different results were produced using data from Cole et al., (1984). In that study, one of 86 nationwide urban runoff samples showed PCBs with a concentration of 0.03 µg/L. Applying this value to the Galveston Bay watershed yielded PCB washoff of less than one kg/yr. The reason for this discrepancy is not known.

Loadings to the Upper Houston Ship Channel

Loadings to the upper Houston Ship Channel (upstream from the mouth of the San Jacinto River) are given in TABLE 6.6, with relative contributions from the five sources shown in the form of pie charts for selected constituents (FIGURE 6.25). Results for this portion of the bay system reflect a high percentage of the total point and nonpoint sources entering the system, but none of the effects from the bay's two largest rivers.

Almost all (96 percent) of the total suspended solids loadings to the Houston Ship channel were caused by local nonpoint sources, compared to about 50 percent for the entire bay system.

Although numerous major municipal and industrial point sources discharge to the upper Houston Ship Channel, point sources were responsible for only 22 percent of the total annual BOD loading, with nonpoint sources contributing 77 percent of the load. This reflects substantial BOD reductions in recent years (see FIGURE 6.27). Municipal point sources were the largest contributors of nitrogen and phosphorus, with 64 percent and 79 percent respectively. Industrial dischargers were responsible for only 11 percent of the total nitrogen loading and ten percent of the total phosphorus loading to the channel.

Municipal point sources contributed over half of the total loading for three metals (total arsenic, total cadmium, and total chromium) to the Houston Ship Channel. Nonpoint sources were responsible for most of the total lead, total mercury, and total zinc loadings to the channel. This finding contrasts with the bay-wide domination of the Trinity River metals loadings. Loadings from the Trinity are delivered in low concentrations in a high volume of water, while loadings to the Houston Ship Channel, a limited area with limited circulation, may contribute to higher ambient concentrations, particularly in sediments.

Point sources of PCBs on the upper Houston Ship Channel totaled 15.7 kg/yr (Armstrong and Ward, 1994), while the Trinity River provided 38 kg/yr. The best estimate for the total PCB loading to the bay (114.7 kg/yr using Armstrong and Ward's estimate) corresponds to between 0.1 and 13 percent of the total PCBs now trapped in the bay's sediment. The lack of comprehensive data for the Trinity River, San Jacinto River, and point sources prevented a comprehensive analysis for pesticides or PAHs.

Besides the recent analysis presented here, Winslow and Associates (1986) also estimated the sources of pollutant loadings to the Houston Ship Channel for BOD, total suspended solids, ammonia-nitrogen, and total Kjeldahl nitrogen. Two different calculation methods were used to analyze the nonpoint source data they collected, and point sources/collection system loadings were divided into overflows, bypasses, wet weather municipal point source flows, dry and transitional municipal point source flows, and industrial point sources.

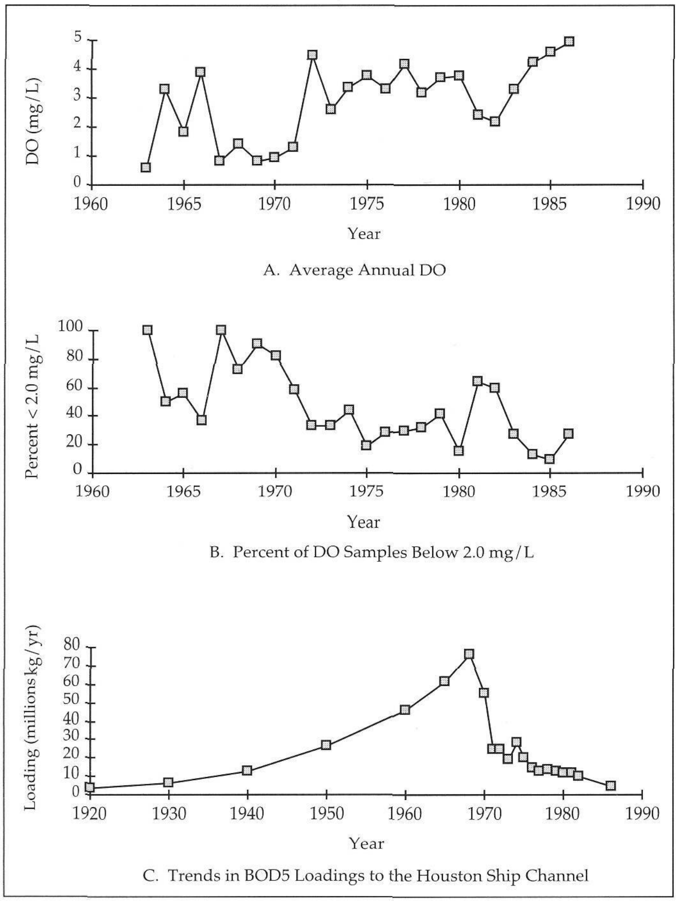
The Winslow and Associates study broadly agrees with the analysis presented here. Using a land use-based "individual component method" for nonpoint sources, they determined that urban runoff was responsible for most of the Ship Channel loading: 73 percent of the annual carbonaceous BOD load to the channel, 90 percent of the TSS, 21 percent of the ammonia, and 52 percent of the TKN. Overflows and bypasses contributed 11 percent or less of these loadings in 1986; since that time the collection system has been improved to reduce the frequency and volume of overflows and bypasses. Municipal point source loadings accounted for about ten percent of the BOD and 66 percent of the ammonia loading. Industrial point sources accounted for less than seven percent of the BOD and five to six percent of the ammonia and TKN loading to the channel.

Other Pollutant Sources

Other sources of pollutants, in addition to those considered in the previous analysis, are likely to have a role in determining water quality in the estuary. A preliminary investigation of rainfall and dustfall loadings was prepared using sampling data reported in Browne et al. (1992). Using typical concentrations for urban and rural settings, loadings from rainfall and dustfall were estimated and compared to the total loadings shown in TABLE 6.5. This comparison indicated that rainfall accounted for less than 15 per-

TABLE 6.6. Upper Houston Ship Channel Analysis: Relative Contributions of Pollutants From Major Sources.

Constituent	Municipal Point Sources	Industrial Point Sources	Lower Watershed Nonpoint Sources	Total
Flow				
Million ac-ft/yr	0.3	0.1	1.0	1.4
(% of Total)	(22)	(5)	(73)	(100)
Total Susp. Solids				
Million Kg/yr	2.6	7.1	208.0	217.7
(% of Total)	(1)	(3)	(96)	(100)
BOD				
Million Kg/yr	1.0	2.2	10.9	14.1
(% of Total)	(7)	(16)	(77)	(100)
Oil and Grease				
Million Kg/yr	5.7	0.6	8.9	15.2
(% of Total)	(38)	(4)	(59)	(100)
Total Nitrogen				
Million Kg/yr	7.1	1.3	2.7	11.1
(% of Total)	(64)	(11)	(24)	(100)
Total Phosphorus				
Million Kg/yr	3.6	0.4	0.5	4.5
(% of Total)	(79)	(10)	(11)	(100)
Total Arsenic				
1,000 Kg/yr	16.3	3.8	10.3	30.4
(% of Total)	(54)	(13)	(34)	(100)
Total Cadmium				
1,000 Kg/yr	5.6	0.8	1.9	8.3
(% of Total)	(68)	(9)	(23)	(100)
Total Chromium				
1,000 Kg/yr	21.8	10.3	3.5	35.6
(% of Total)	(61)	(29)	(10)	(100)
Total Copper				
1,000 Kg/yr	18.8	9.2	17.4	45.4
(% of Total)	(41)	(20)	(38)	(100)
Total Lead				
1,000 Kg/yr	23.1	2.3	48.7	74.1
(% of Total)	(31)	(3)	(66)	(100)
Total Mercury				
1,000 Kg/yr	0.00	0.06	0.31	0.37
(% of Total)	(0)	(16)	(84)	(100)
Total Zinc				
1,000 Kg/yr	84.4	29.6	139.9	253.9
(% of Total)	(33)	(12)	(55)	(100)



Source: Armstrong and Ward, 1994; Stanley, 1992

FIGURE 6.27. Dissolved oxygen improvements in the upper Houston Ship Channel resulting from improved wastewater treatment. Increased dissolved oxygen (a), and a reduction in the frequency of dissolved oxygen depletion below 2.0mg/L (b) resulted from a greater than 95 percent reduction in BOD loading (c). Data is for segment 1006 (Greens Bayou to San Jacinto River). In spite of these improvements, low dissolved oxygen (particularly near the bottom) remains a concern throughout the upper ship channel.

cent of the total loading for three indicator parameters: total nitrate/nitrite (12 percent), lead (less than one percent), and cadmium (nine percent). Surprisingly, the reported dustfall rate of 32 tons per sq mi per month for the Gulf Coast was estimated to contribute almost 23 percent of the total sediment load to the bay if the entire 600 sq mi area of the bay is assumed to be subject to this deposition rate. In reality, much lower deposition rates are probably experienced in the open bay or at seaward locations farther from sources.

Groundwater may also affect the quality of Galveston Bay. Jensen (1992) reports the contribution of septic tanks to the fecal coliform loading to the bay as negligible. Groundwater pollution from hazardous waste sites has been identified as a possible source of toxicants, but data from existing groundwater regulatory programs has not been compiled to provide bay-wide groundwater loading. Chapter Nine identifies contamination of Clear Creek by toxic organics in the vicinity of the Brio Superfund Site. Future work on this topic is planned as part of the Texas Clean Rivers Program.

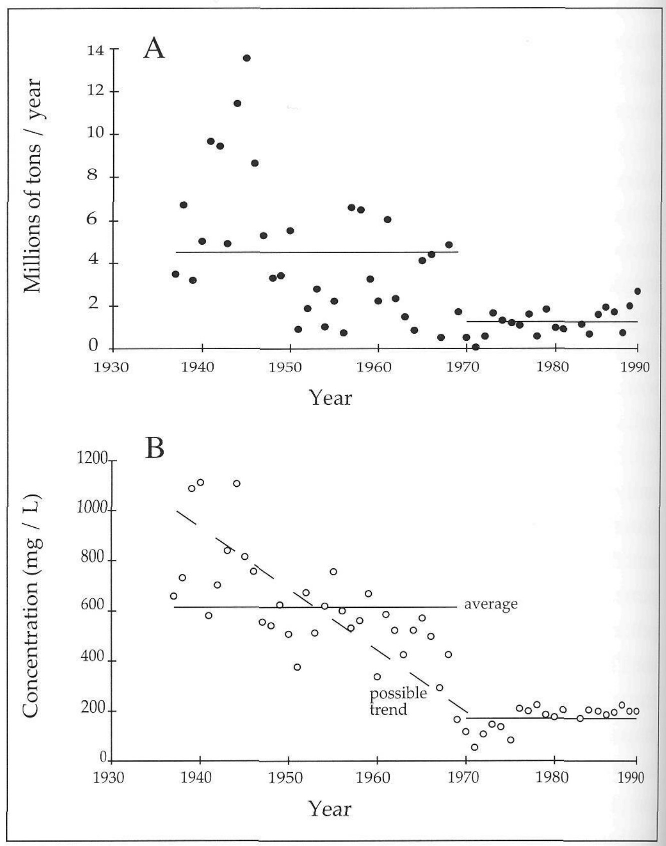
Finally, three recent incidents have resulted in major spilled cargoes in the Houston Ship Channel inside of the Galveston Bay Estuary:

> In 1989, the Tank Barge *Coastal 2514* spilled 6,000 barrels of oil slurry.
>
> In 1990, the Tank Barge *Apex Marine 3417* released 700,000 gallons of number five oil.
>
> Also in 1990, the Bottle Barge *Duval II* spilled 2,800 tons of molten sulfur.

These and numerous smaller oil and chemical spills constitute another source of pollution.

Patterns at the Ecosystem Level

Water quality is controlled by a number of interrelated processes, **feedback loops** and numerous components which are difficult to measure. This complicates the analysis of cause-and-effect mechanisms at the ecosystem level. Because of this complexity, many of the observed trends are difficult to explain. In Galveston Bay, however, three systematic trends have been linked



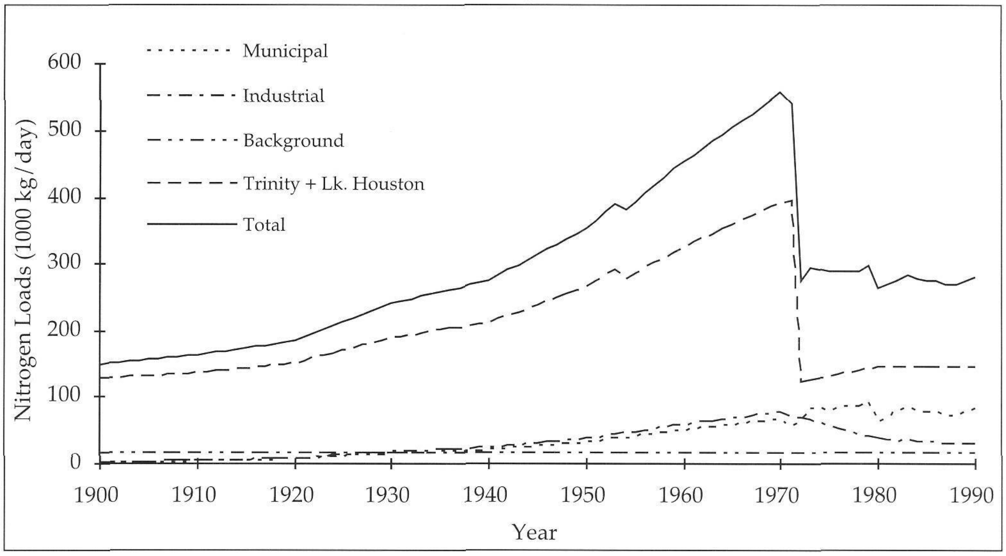
Source: Armstrong and Ward, 1994

FIGURE 6.26. Historical variation in the silt load of the Trinity River at Romayor. This location is just downstream of Lake Livingston, a major reservoir with nearly the same water volume as Galveston Bay. The data reveal a major reduction in Trinity River silt coinciding with completion of the reservoir, which reached normal pool level in 1973. Lake Livingston, and Lake Houston on the San Jacinto, serve as efficient sediment traps and thereby also capture other constituents associated with silt particles, for example phosphorus.

to cause-and-effect mechanisms. These trends, described below, illustrate ecosystem responses to external changes in human activity.

Reduced TSS Concentrations Due to Lake Livingston

As shown in FIGURE 6.26, the current sediment load in the Trinity River is about two-thirds less than the historical sediment load (1930s and 1970s). Two possible mechanisms involved are: 1) the construction of Lake Livingston; and 2) changing land use practices and construction of other reservoirs in the upper part of the Trinity River watershed (Ward and Armstrong, 1992).

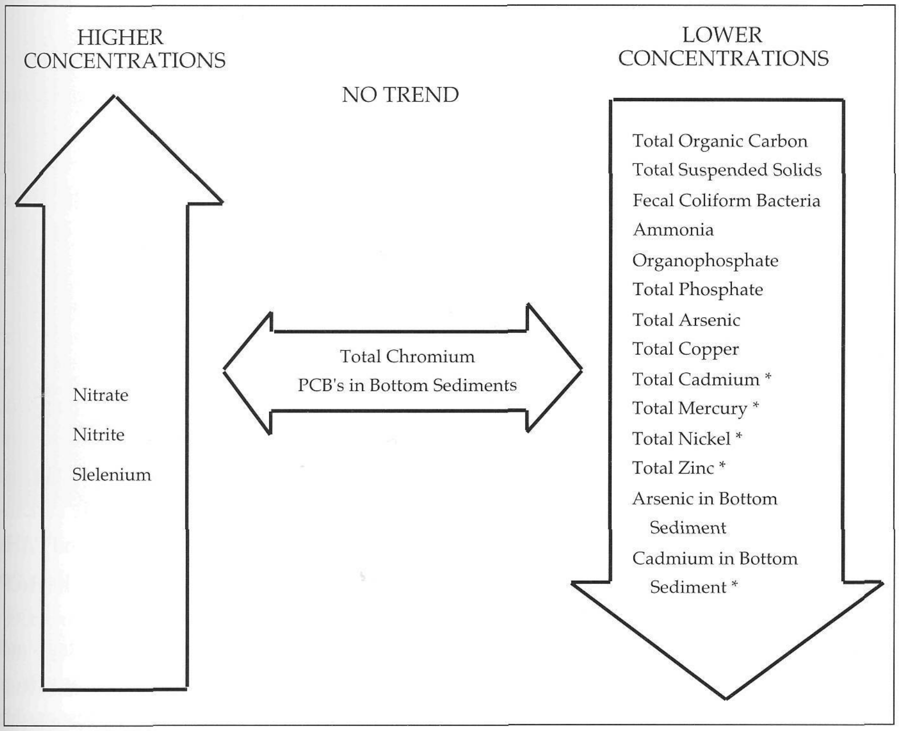


Source: Jensen et al., 1992

FIGURE 6.29. Nitrogen loads in the Galveston Bay system. Reduced nitrogen loading in the 1970s resulted from the construction and upgrading of treatment works triggered by the Federal Water Quality Act. This, combined with the influence of reservoir construction, resulted in nitrogen reductions to approximately 1930s levels. "Background" does not include the Trinity River of Lake Houston.

Lake Livingston construction began in 1968 and water reached design pool level about three years later. To put this reservoir in perspective, it is useful to note that Lake Livingston and Galveston Bay are almost the same volume: two million ac-ft for the lake vs. 2.2 million ac-ft for the bay. The lake has an average hydraulic residence time of 4-5 months, giving it a theoretical sediment-trapping efficiency of more than 50 percent.

Changes in land use practices in the upper watershed are difficult to quantify, although there has been a definite increase in no-till agriculture and implementation of erosion control programs by the U.S. Soil Conservation Service. In addition, a total of 28 major reservoirs have been constructed in the upper Trinity watershed above Lake Livingston with a cumulative storage capacity of about six million ac-ft. Most of these reservoirs were constructed in the 1950s and 1960s and now trap large quantities of sediment that once were carried to the bay.



Source: Crocker, 1993

FIGURE 6.28. Water quality trends in the upper Houston Ship Channel. For most constituents at most locations, improvements have resulted from improved wastewater treatment (asterisks denote improvement at upstream stations only). For trends by station, see FIGURE 6.12.

If a two-thirds reduction in sediment load from the Trinity River is applied to the data in TABLE 6.5, then it appears that the changes in the Trinity River have decreased the overall sediment load to the bay by 40 to 50 percent. Over the same time period, total suspended solids concentrations in the open bay have also declined to a level about one-third of their value 25 years ago. Although in-bay factors may have also contributed to this decline, the primary mechanism is probably reduced sediment loads from the Trinity River.

Improved Houston Ship Channel Water Quality from Wastewater Treatment

As described in the introduction, the Houston Ship Channel was one of the most polluted bodies of water in the world in 1970, due to the discharge of massive volumes of pollutants from industrial, municipal, and nonpoint sources. In 1968, over 76 million kilograms of biochemical oxygen demand were discharged to the upper channel every year, effectively inhibiting the presence of aquatic life.

Then in 1971, the Environmental Protection Agency and the forerunner of the Texas Natural Resource Conservation Commission implemented a stringent program to improve wastewater treatment. Industries were the first to respond, followed by upgraded municipal discharges in the early 1980s (such as the start-up of the City of Houston's 69th Street Plant in 1983). By 1990 the BOD loading to the channel had been reduced by over 95 percent to 3.1 million kg/yr (FIGURE 6.27). The current BOD loading is approximately the same as the loading to the channel in the 1920s (Armstrong and Ward, 1994), an amazing water pollution control achievement.

The effect of BOD reduction on the water quality of the Houston Ship Channel has been significant. The average surface dissolved oxygen concentration in the lower channel is now above five mg/L, while the percentage of samples below two mg/L has been reduced considerably (FIGURE 6.27). The concentration of a number of other pollutants in the channel has also been reduced, and most constituents that have increased in concentration are also associated with improved wastewater treatment (FIGURE 6.28).

Changing Nitrogen Loads to the Bay

Jensen et al. (1991) provided a long-term estimate for the change in total nitrogen loads to the bay (FIGURE 6.29). Their period of record was from 1900 to 1990, and they included simplified estimates for local industrial point sources, local municipal point sources, "background" concentrations (local nonpoint sources), and Lake Houston/Trinity River. Note that the Lake Houston/Trinity River data reflect a combination of point sources and nonpoint sources from the upper watersheds.

The analysis identified a four-fold increase in total nitrogen loading to the bay from 1900 to 1973, primarily a result of slowly increasing nitrogen concentrations in the Trinity River. Only 10-20 percent of the total increase during this 73-year period was caused by higher loadings from local industrial and municipal point sources that started growing rapidly after 1950.

After 1973, several things happened that greatly reduced nitrogen loads to the bay. Most importantly, the Lake Livingston dam was constructed and reduced overall nitrogen loadings by over 50 percent (due to sedimentation, **denitrification**, and phytoplankton uptake). Starting in the early 1970s, there was also a reduction in industrial nitrogen loadings, although this reduction was dwarfed by the overall reduction caused by Lake Livingston.

Finally, total nitrogen loads from municipal sources leveled off after 1973. Further reductions were limited by the nature of the treatment process. Secondary treatment does not include nitrogen removal (while waste treatment processes result in the conversion of ammonia to nitrate, total nitrogen is unchanged). Because some of the channel dischargers were already on secondary treatment, the overall effect of improved wastewater treatment in the 1970s was much more apparent for BOD than total nitrogen.

The long-term reduction in nitrogen loading is a significant process for Galveston Bay, because primary productivity of phytoplankton (the basis for the entire food chain) is conventionally thought to be nitrogen-limited in coastal marine systems. During the same time period that nitrogen loads were reduced, there was an apparent decline in phytoplankton abundance (as measured by chlorophyll-*a* reductions of over 50 percent in the past 20 years). Overall ramifications include a possible reduction in dissolved oxygen in some areas of the bay possibly due to less photosynthetic activity, and a speculated (and debated) future crash in oyster populations due to lack of food supply (see Chapter Seven).

SUMMARY

The Galveston Bay system is characterized by good water quality in open bay waters. Water and sediment quality problems, where they occur, are primarily found in the western, urbanized tributaries. Water quality in these locations has shown significant improvement over the past 20 years because of improved wastewater treatment by point source dischargers. Nonpoint sources, therefore, represent the greatest challenge for future water quality improvements.

Significant water quality improvements have been made in the bay's largest and most problematic urban tributary–the upper Houston Ship Channel. Prior to 1970 much of the Ship Channel above the mouth of the San Jacinto River was a lifeless body of water with little or no dissolved oxygen. A 95 percent reduction in the discharge of biological oxygen demand has reduced loadings to the levels seen in the 1920s. As a result, dissolved oxygen concentrations have increased significantly, permitting the return of some aquatic life in the upper Houston Ship Channel (see Chapter Eight). Despite improvements, some reaches of the upper Houston Ship Channel continue to exhibit low dissolved oxygen levels in the one to two mg/L range, particularly near the bottom.

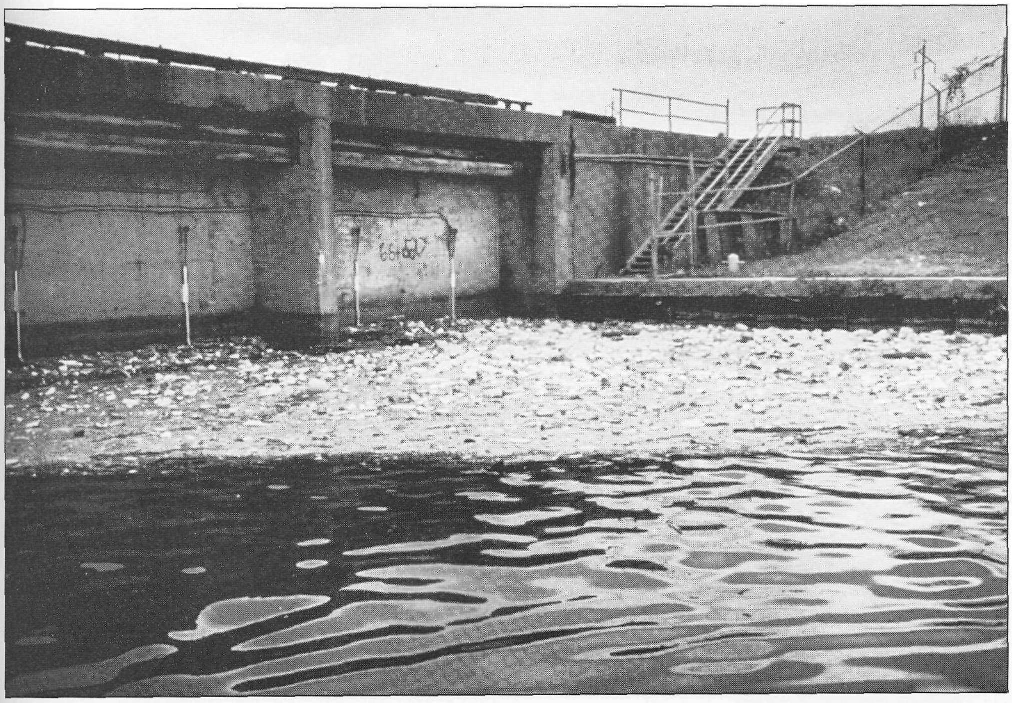
Although data are sparse, metals have apparently also undergone a general decline in both water and sediments of the upper estuary where contamination has traditionally been greatest. However, possible shortcomings in the traditional analytical methods for metals make interpretation of metals data difficult. If the decline in metals is real, the possible explanations include improved industrial wastewater treatment, and removal of contaminated sediments by upland confinement of dredged material.

PCBs and PAHs have been identified as particular water quality problems due to bioaccumulation by aquatic organisms (see Chapter Nine). Available data indicate that: 1) most of the PCBs and PAHs are derived from urban runoff, although there is one discharger of PCBs to the bay; 2) some of the water samples collected in the Houston Ship Channel violate state criteria for safe concentrations of PCBs; and 3) the total concentration of PCBs and PAHs now stored in bay sediments is probably much higher than the annual delivery of these compounds to the bay.

A bay-wide analysis of five major sources of pollutants and other water quality constituents revealed that the Trinity River (which includes both point and nonpoint sources) was responsible for almost half of the sediment, nitrogen, and metals loadings to the bay. These loads are delivered in diluted concentrations and do not appear to be elevating ambient levels in either water or sediments.

Source: Galveston Bay National Estuary Program

The bay's greatest water quality challenge is control of nonpoint sources of pollution. Storm water washing over streets, parking lots, and residential neighborhoods contains such contaminants as oil and grease, fertilizers, herbicides, and pesticides. With each rain, storm sewers (above) discharge these materials to the urban bayous (below), where floatable trash becomes an eyesore.



Source: Russell W. Kiesling

Local nonpoint sources contributed more than half of the sediment, BOD, oil and grease, and phosphorus loadings, often to portions of the bay with limited flushing. Industrial point sources contributed less than seven percent of any of the total loading of any pollutant, including heavy metals and BOD, while municipal point sources were responsible for about one-third of the total oil and grease, total nitrogen, and total phosphorus loads.

The same pollutant source analysis, applied to just the upper Houston Ship Channel above the mouth of the San Jacinto river, revealed an even more dramatic dominance of nonpoint sources for some constituents (e.g. BOD). Municipal point sources, however, dominated the loading to this area for nutrients and metals, with industry contributions of most conventional parameters relatively minor.

Overall, the open bay is cooler, less saline, and much clearer than it was 30 years ago. Although the temperature and salinity changes do not have a simple explanation, the reduction in total suspended solids is probably due to the completion of Lake Livingston in 1973. This reservoir, which holds about the same volume of water as Galveston Bay, traps sediments from the upper watershed, reducing suspended solids concentrations in the bay to about one-third their value in the late 1960s.

Lake Livingston is probably also responsible for a 40-50 percent reduction in total nitrogen loads to the bay and the subsequent decline in nitrate and ammonia concentrations in open bay waters. Although wastewater treatment improvements likely also had role, the overall annual nutrient reduction caused by Lake Livingston is probably several times larger than the reduction from any other cause. All told, the Lake Livingston dam has appeared to reverse the steadily increasing trend of nitrogen loadings to the bay noted since 1900 (primarily from the Trinity River), and now nitrogen loads to Galveston Bay are about what they were in the 1930s.

Lower nitrogen concentrations in the open bay are probably the main reason for the observed 50 percent reduction in phytoplankton biomass (indicated by chlorophyll-*a* over the past 30 years). A continued decrease in phytoplankton populations, if it occurs, could affect the bay's food web (reducing the oyster food supply, for example), or could be hailed as a success story for management, returning the bay to a more nearly pristine nutrient and productivity level.

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